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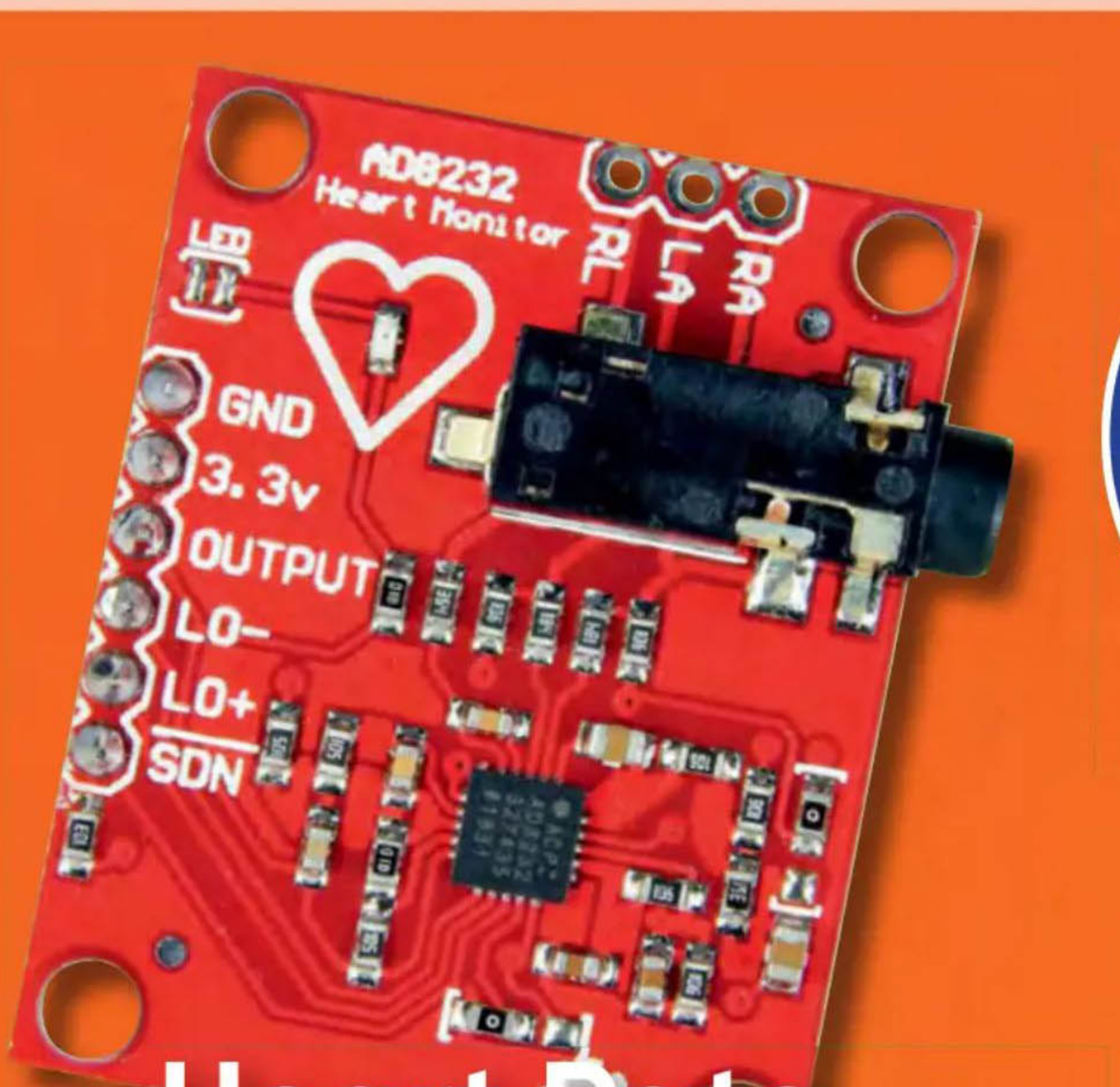
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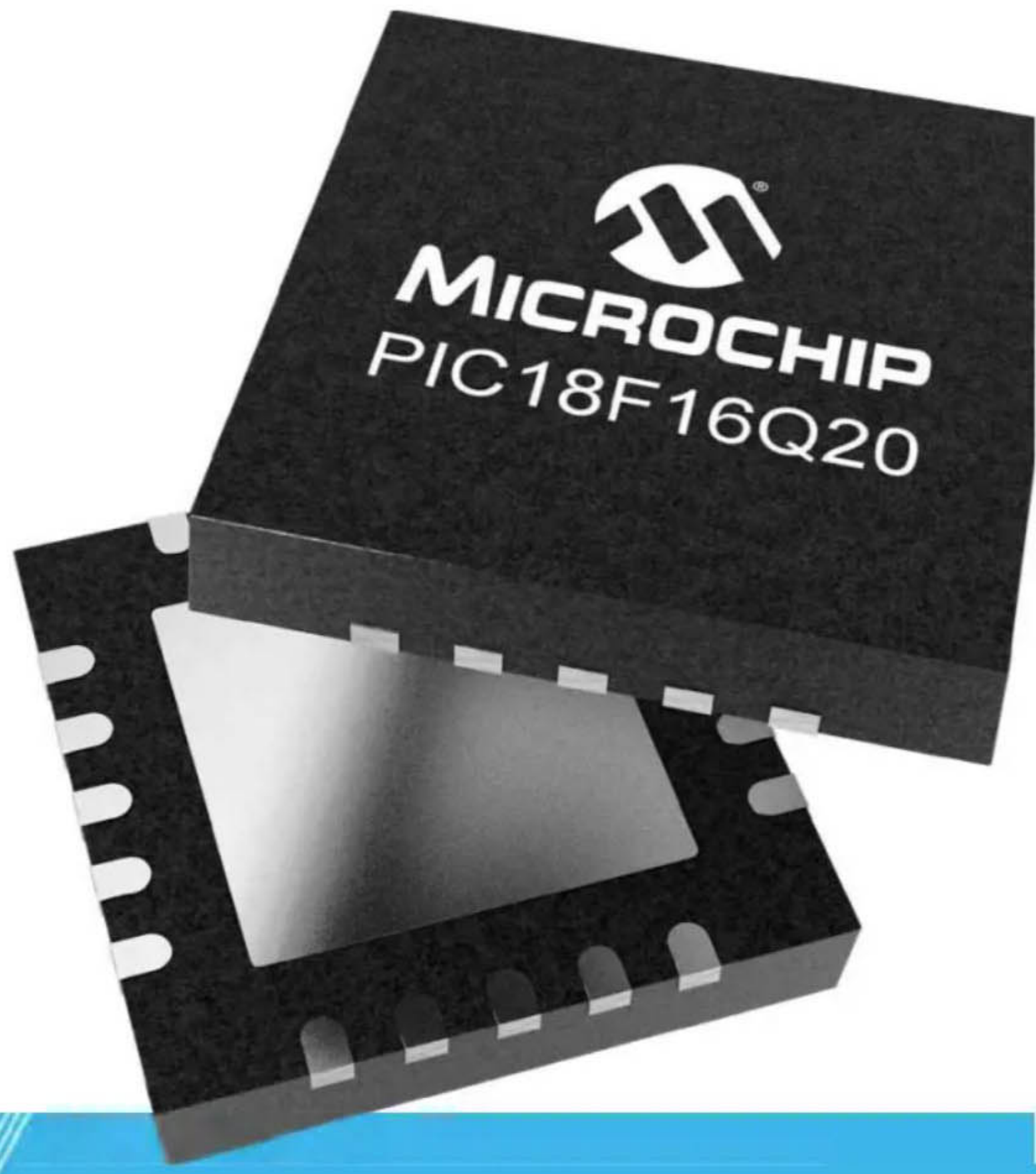

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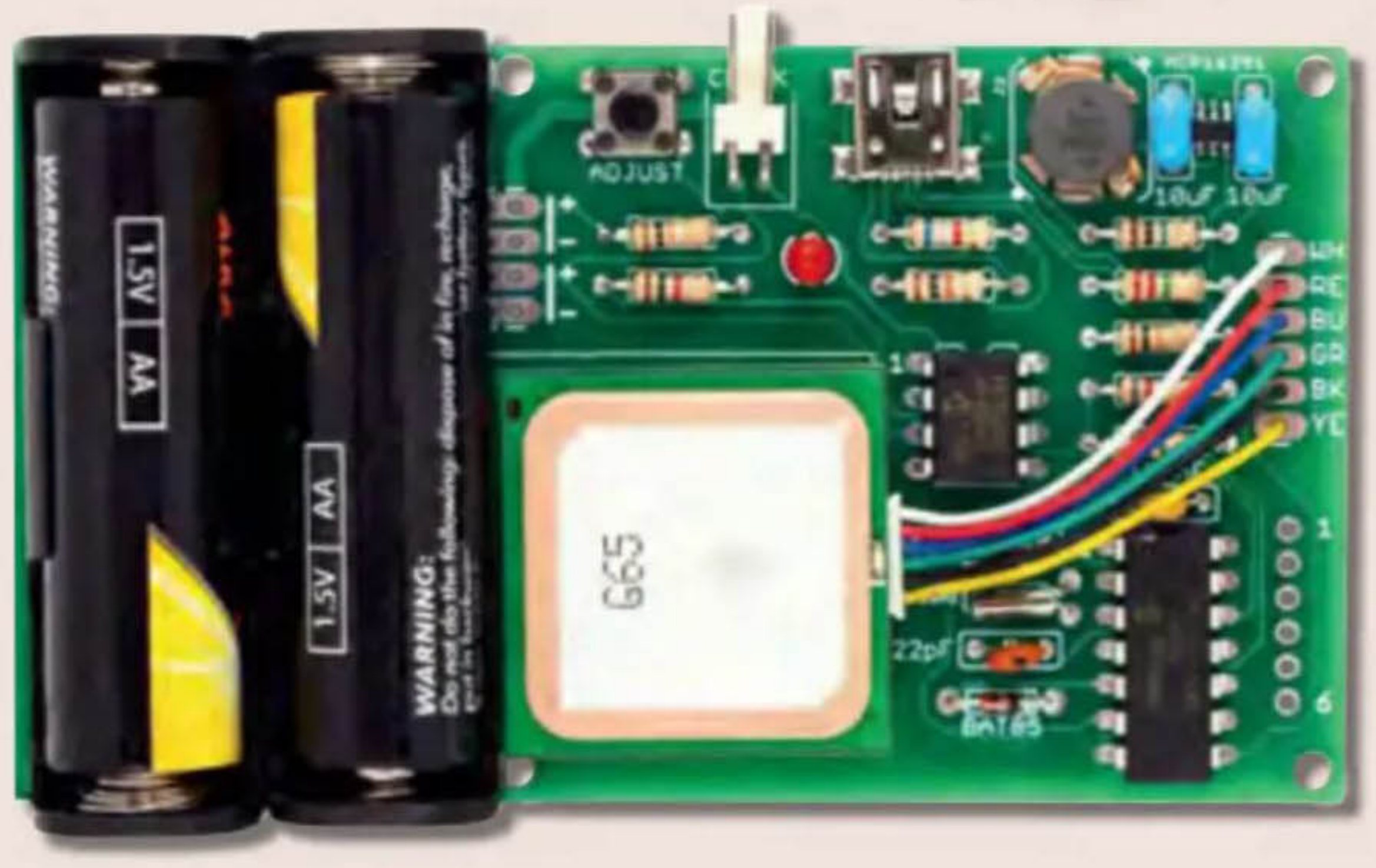

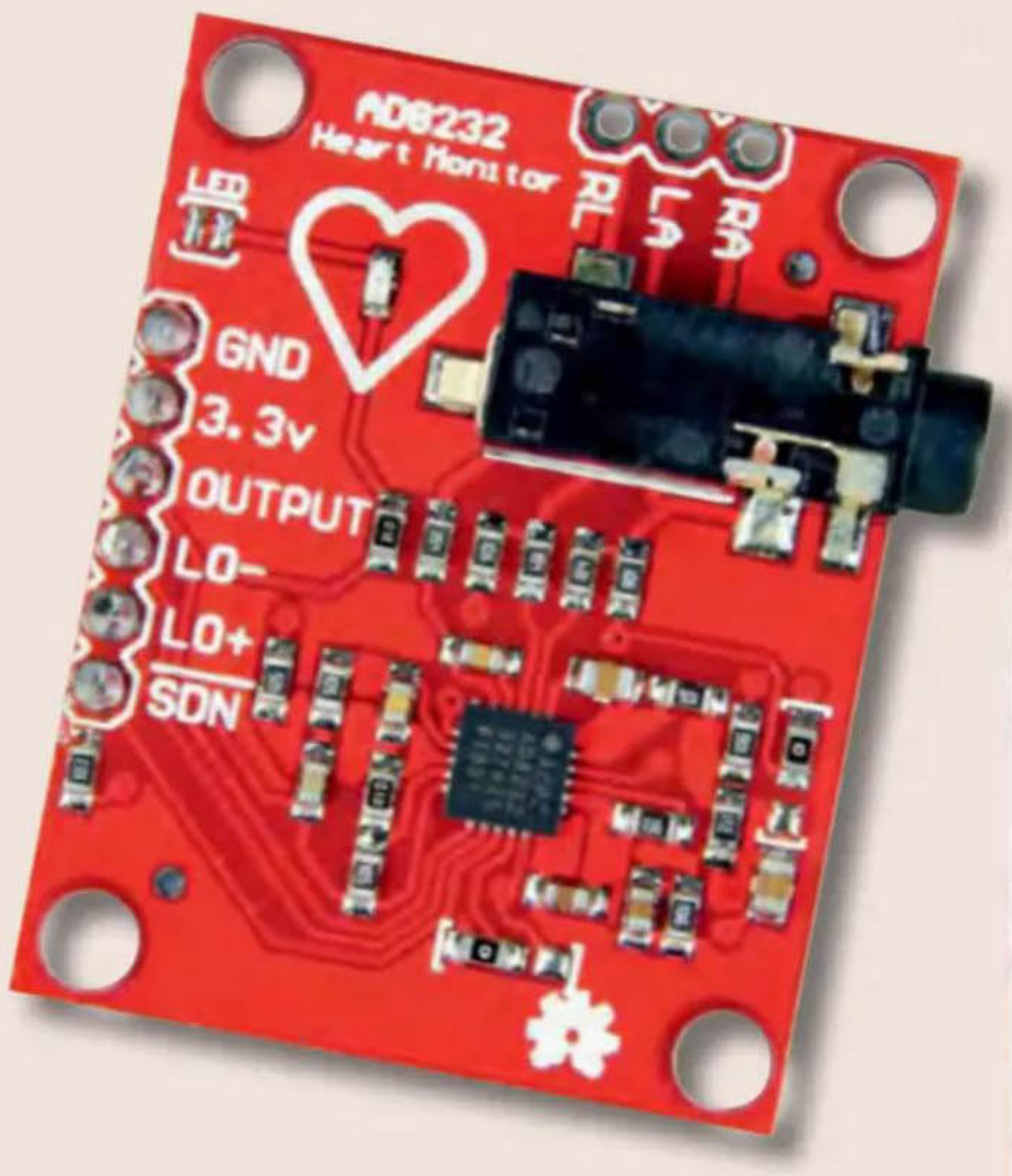

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The July 2024 issue of *Practical Electronics* will be published on Thursday, 6 June 2024 – see page 72.

WIRELESS FOR THE WARRIOR

by LOUIS MEULSTEE

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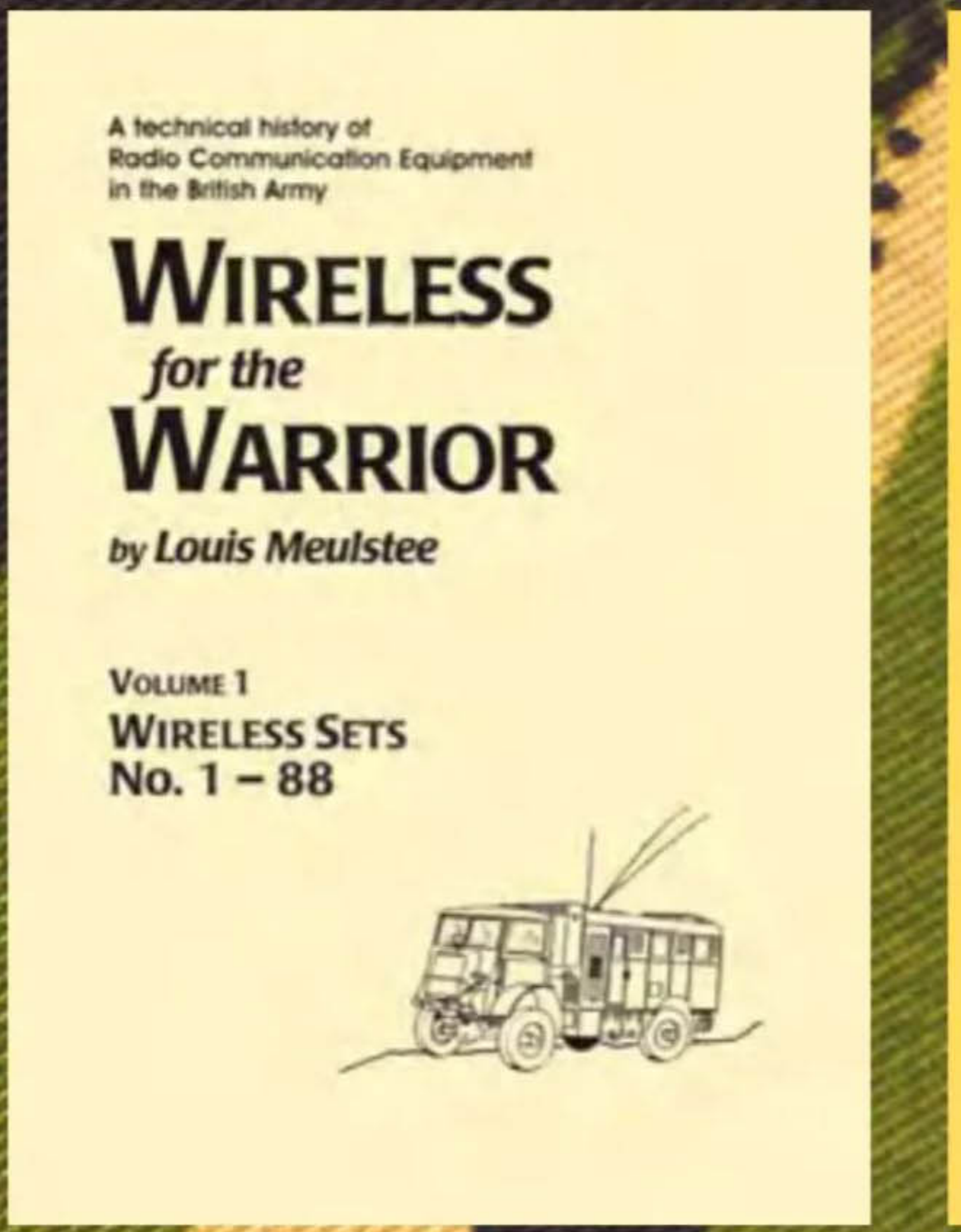
***Volume 4* covers clandestine, agent or 'spy' radio equipment, sets which were used by special forces, partisans, resistance, 'stay behind' organisations, Australian Coast Watchers and the diplomatic service. Plus, selected associated power sources, RDF and intercept receivers, bugs and radar beacons.**



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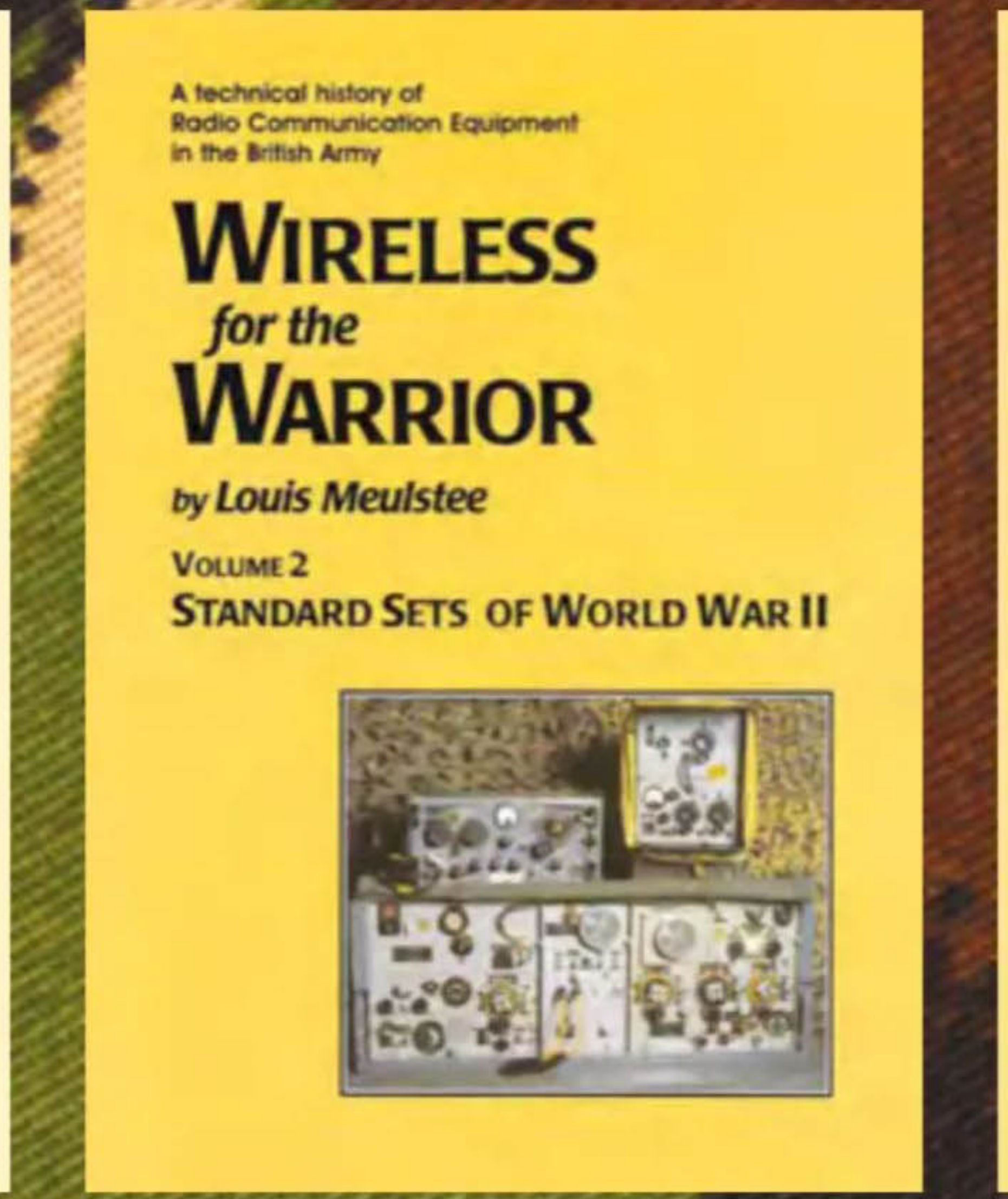

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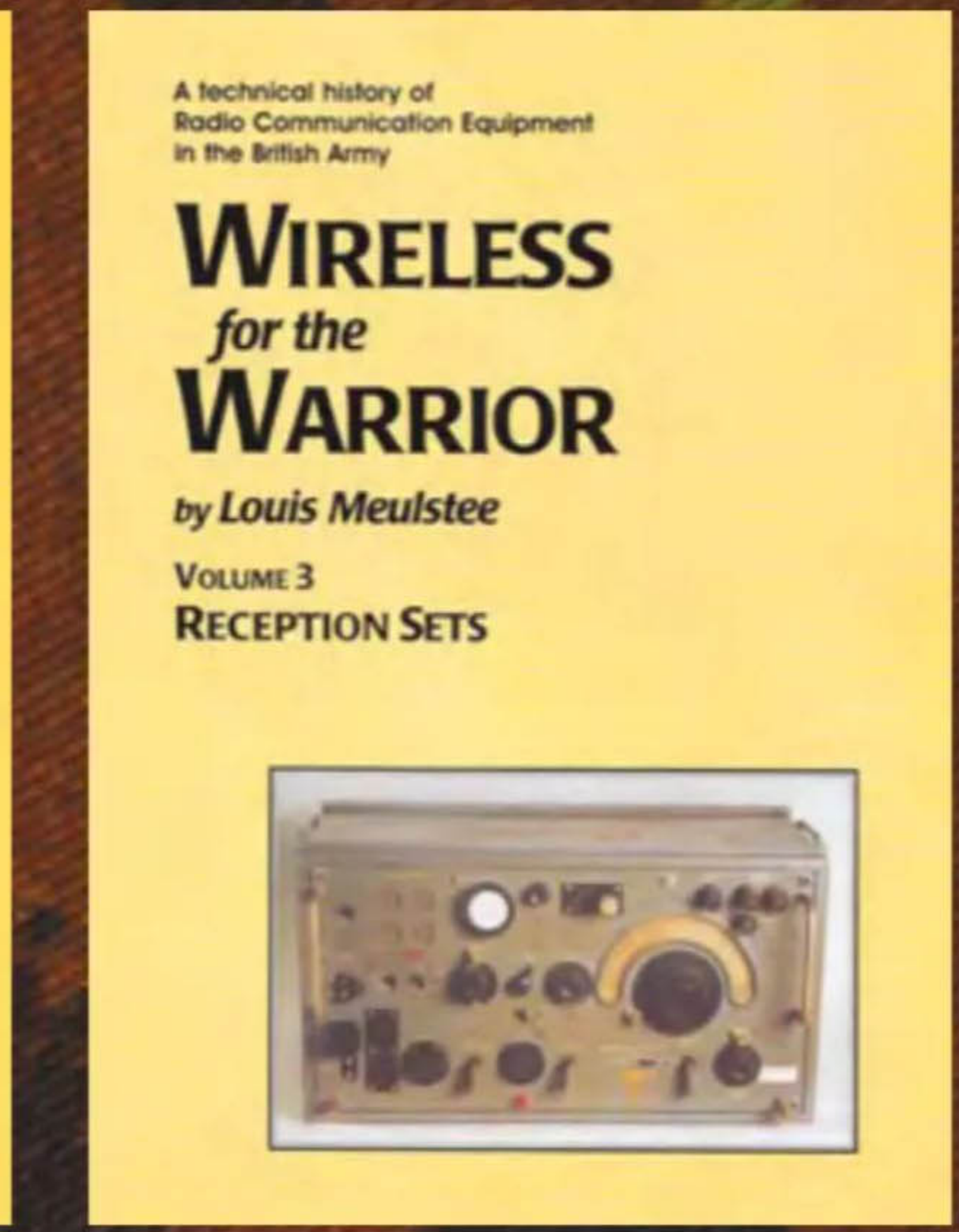

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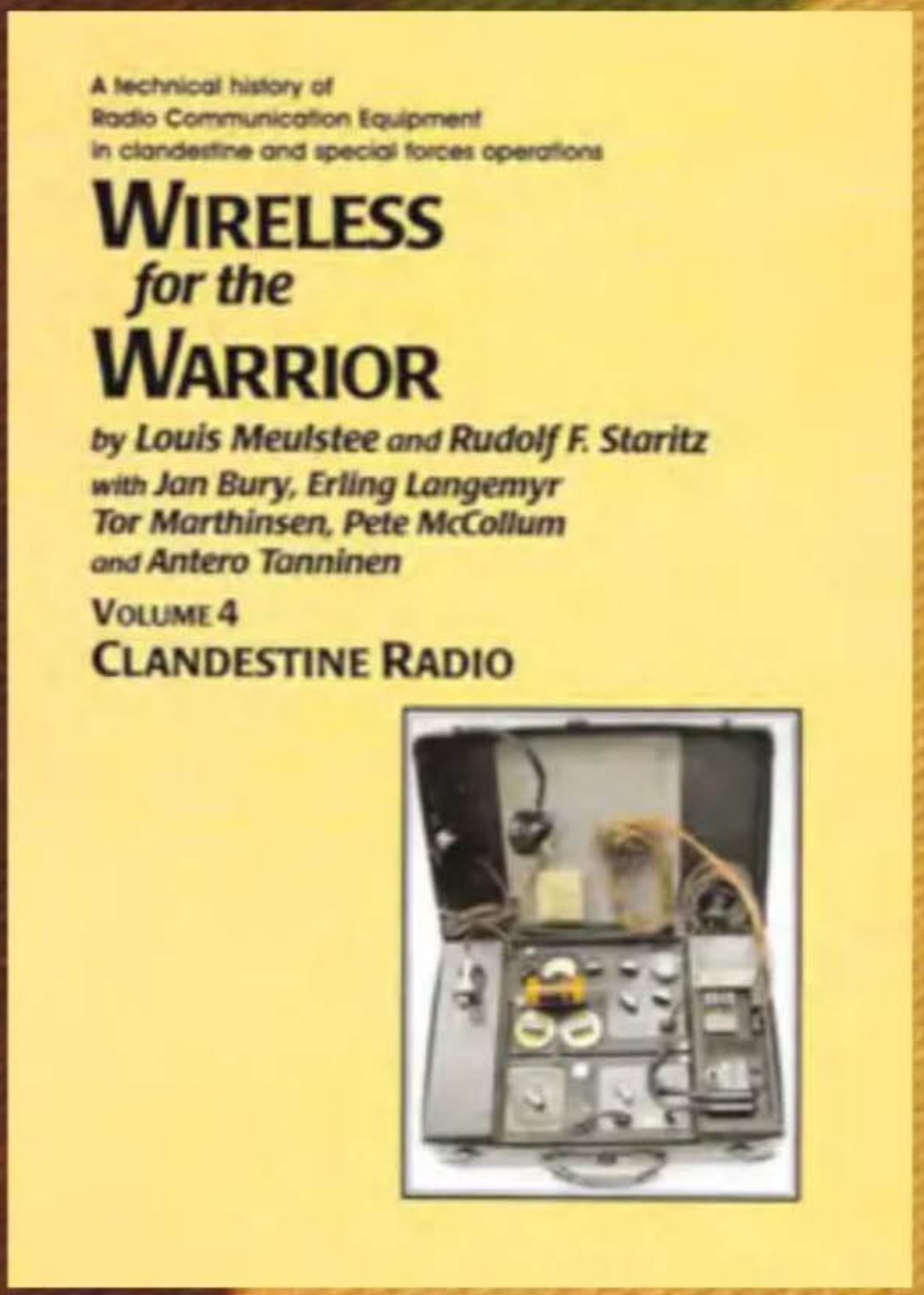

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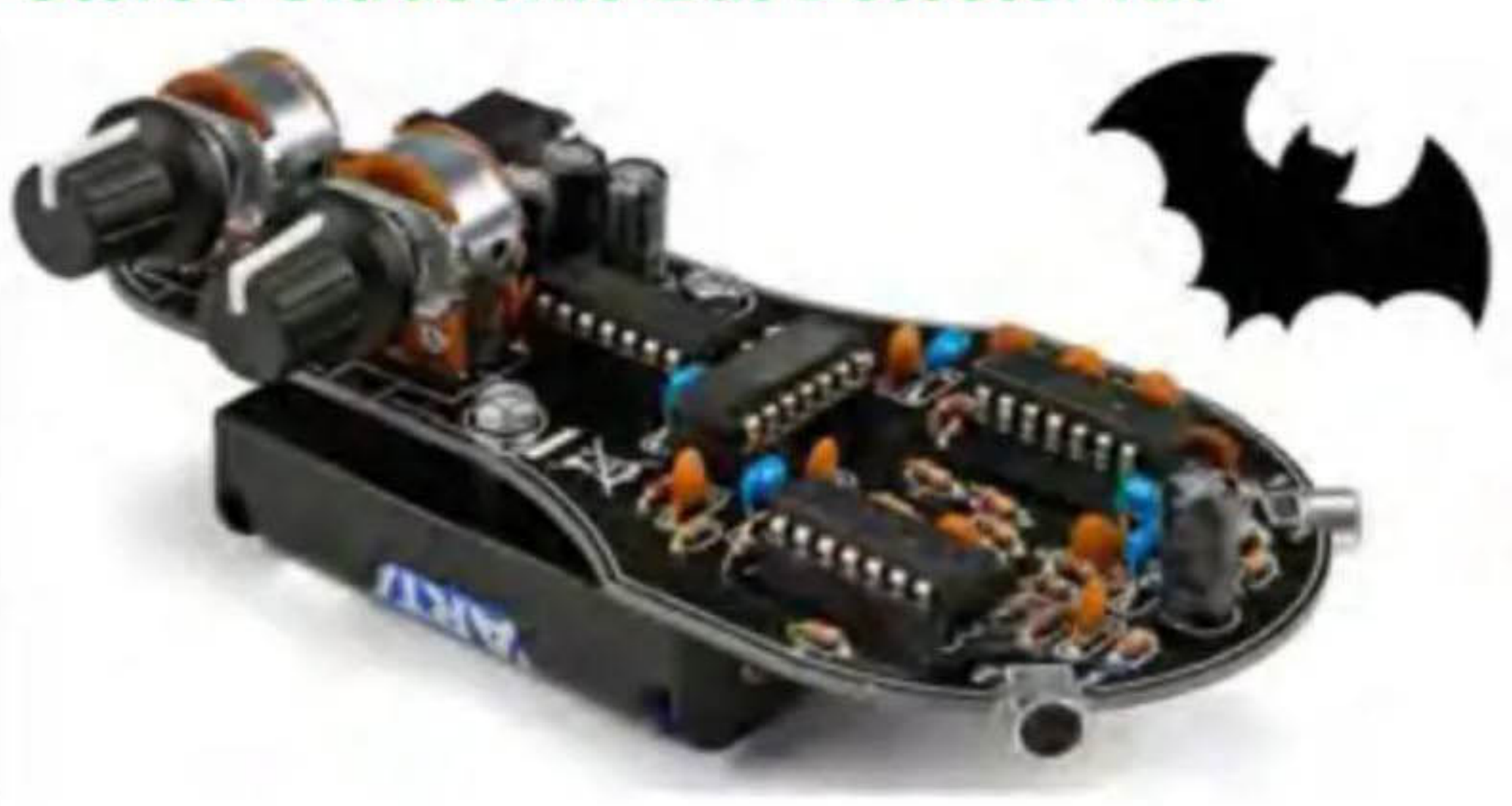
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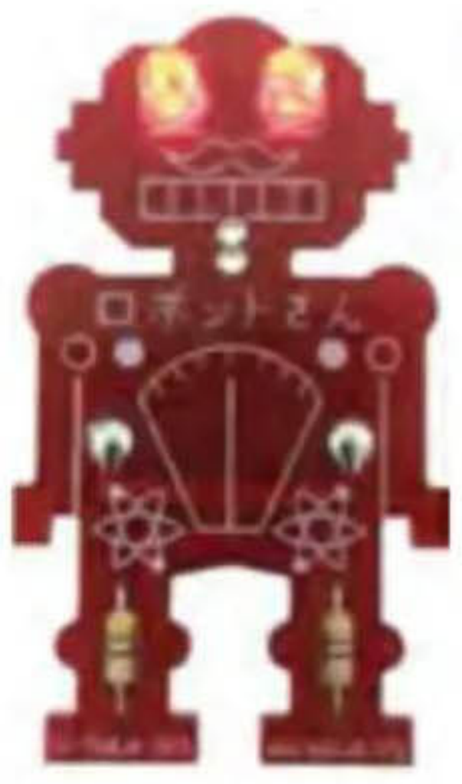
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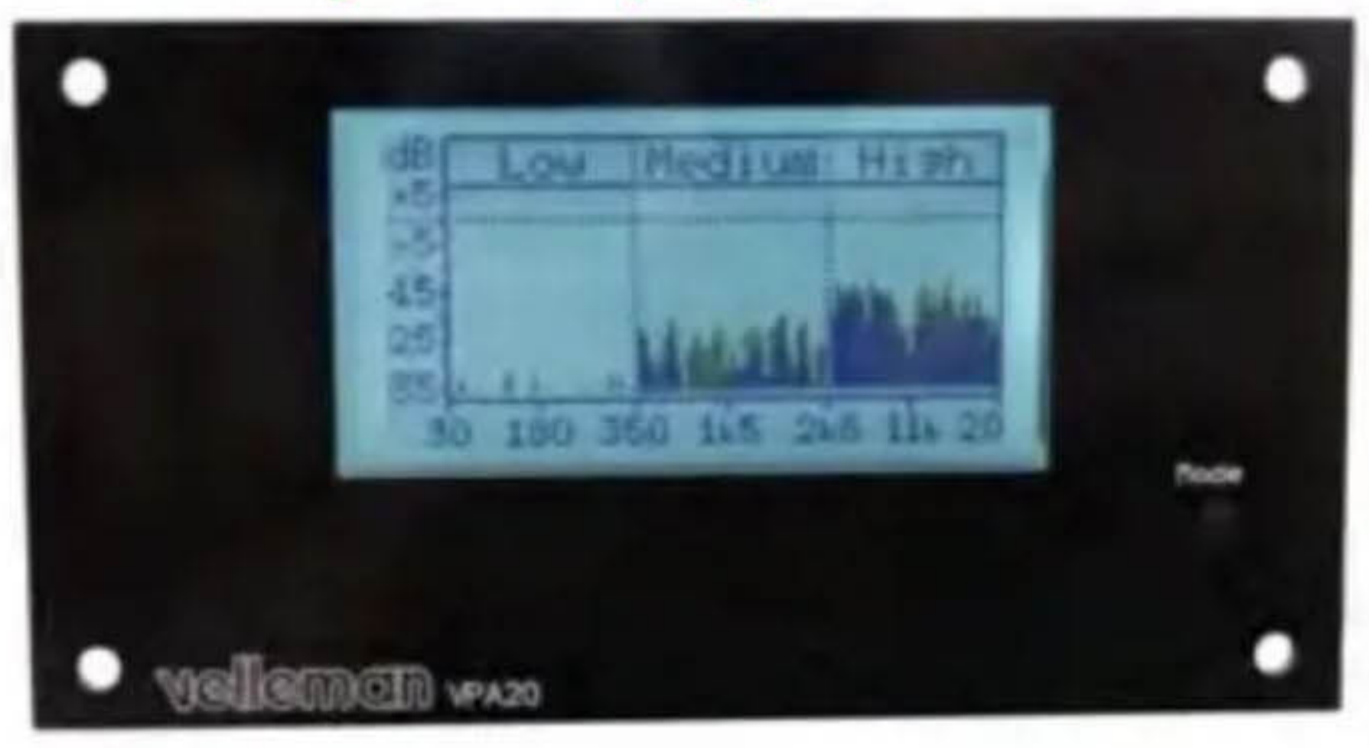
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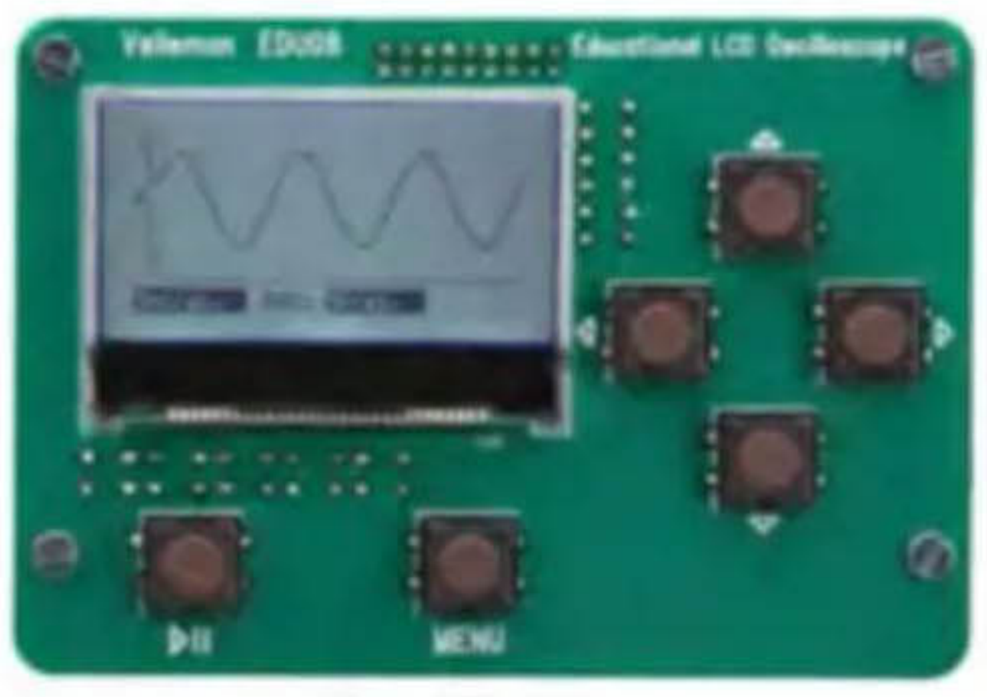
Build your own LCD oscilloscope with this exciting new kit. Learn how to read signals. See the electronic signals you learn about displayed on your own LCD oscilloscope. Despite the low cost, this oscilloscope kit has a lot of features found on expensive units like signal markers, frequency, dB, true RMS readouts and more. A powerful auto-setup function will get you going in a flash!
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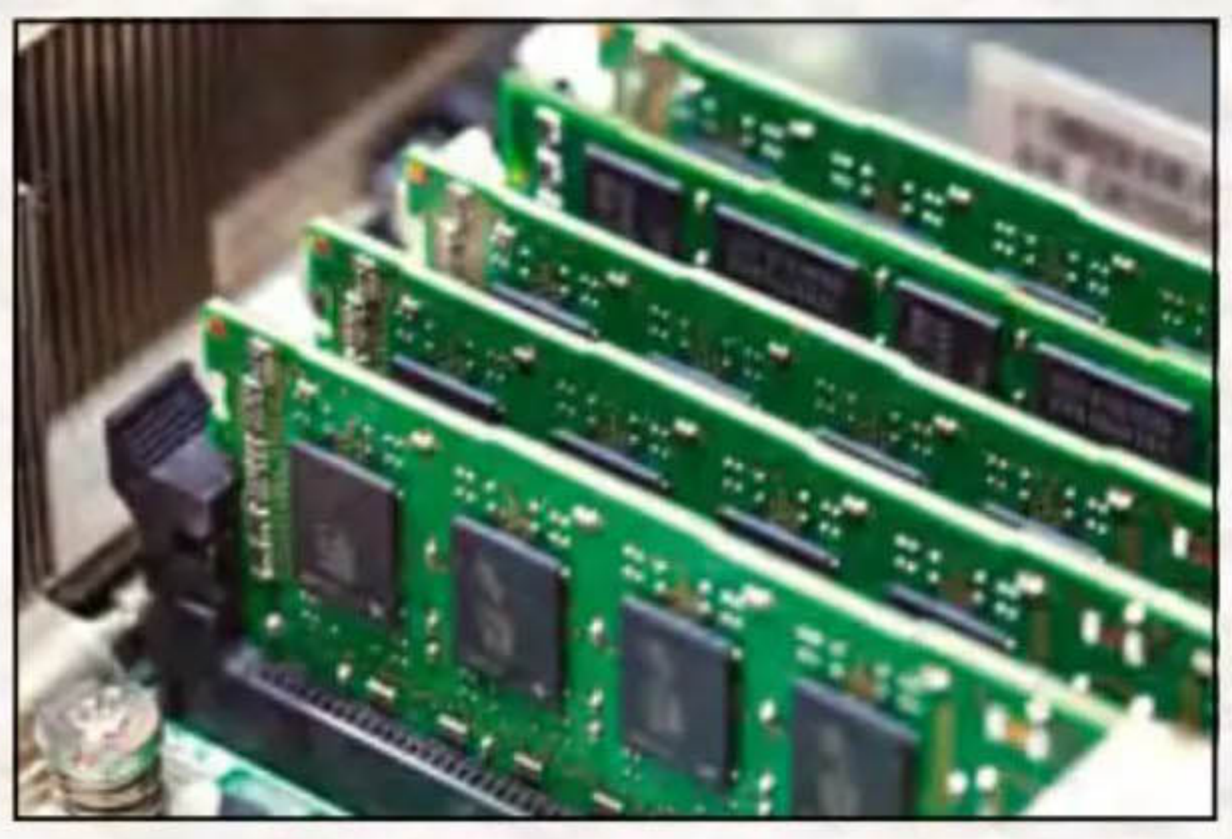

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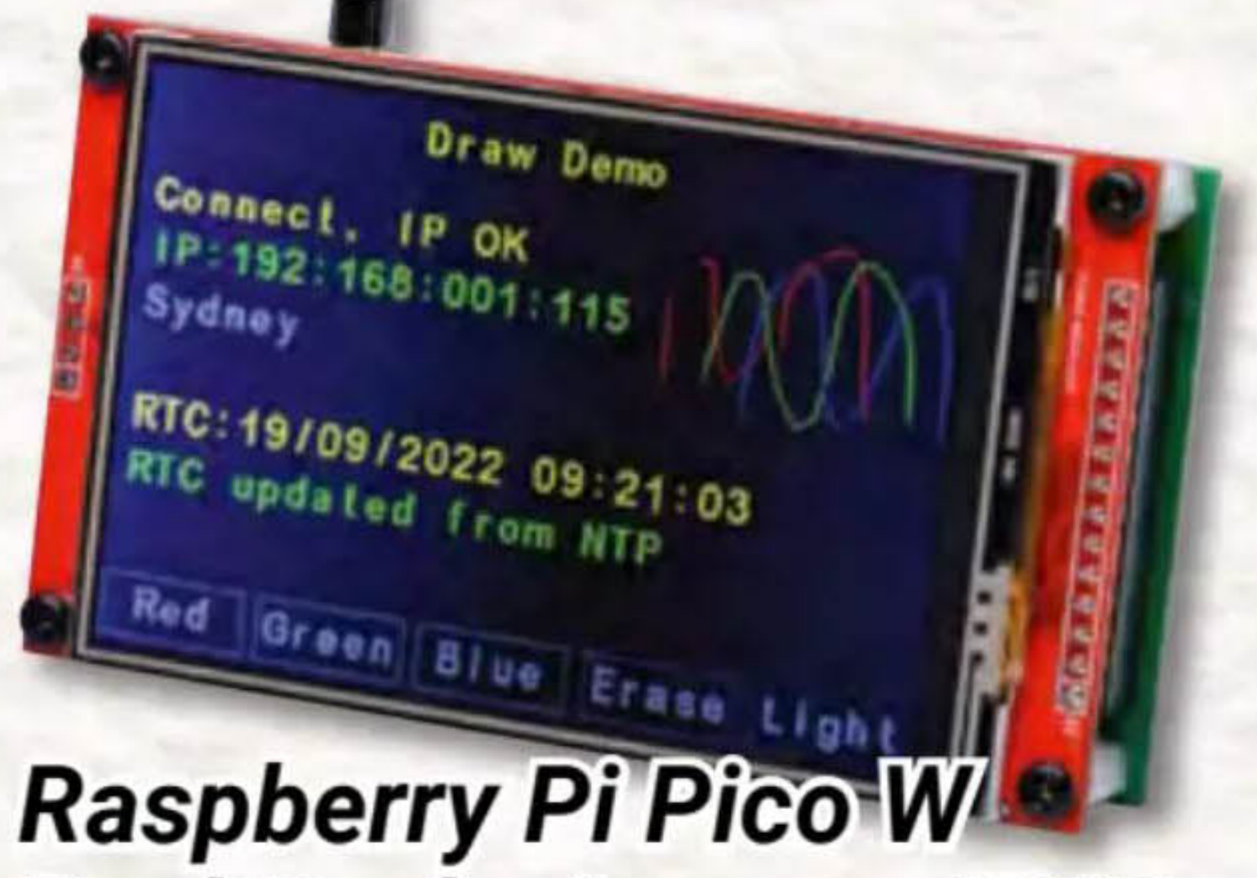
Draw Demo
Connect, IP OK
IP:192:168:001:115
Sydney
RTC:19/09/2022 09:21:03
RTC updated from NTP
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Editorial

Test your speakers!

Of all the elements in a Hi-Fi set up, the loudspeaker is the most difficult to test. Amplifiers, preamplifiers and power amplifiers may contain dozens, perhaps even hundreds of components, but they have a signal output that is straightforward to check electronically. The big problem with speakers is that their output is essentially mechanical – sound – which is not easy to analyse. Yes, the ultimate arbiters of speakers are your ears, but that is – by definition – a somewhat subjective approach, and you certainly can't 'see' what is going on in terms of frequencies, phase and levels. Add to this the fact that loudspeakers are far and away the least ideal link in the audio chain, with distortion and non-linearity levels that would make an amplifier designer faint, and you have a real test and measurement problem. But it doesn't stop there. Imagine if it mattered where you placed an amplifier or CD player; that the sound changed dramatically if your amp was set up next to or away from the wall. Sounds a little daft, but that is exactly what happens with speakers – it really does matter where they are positioned.

All of this is a rather longwinded way of saying that testing speakers is challenging; so difficult that many of us don't bother. Now though, there is a really nice solution. This month, we have an excellent project that combines analogue electronics, your PC's sound card and some free software to give you all the data you need to *really* understand your loudspeakers. The *Loudspeaker Test Jig* is an audiophile's dream come true – recommended!

The battle for semiconductor supremacy

I'm a little late to this next item, a very readable 2022 book called *Chip War*, by Chris Miller. It sat on my to-read pile for over a year, but having finally got around to it I enjoyed it so much that I thought I'd pass on the recommendation. *Chip War* is a fascinating account of the rise (and in some cases fall) of semiconductor giants; from the original start-ups in the US (Silicon Valley) to the current domination by Taiwanese company TSMC and Dutch lithography leader ASML. It's a truly fascinating story that is far from over, and I'm sure you will enjoy it. It reminded me a little of the wonderful three-part documentary, *Triumph of the Nerds*, which did a superb job of explaining the history of the PC. You can find it on the Internet and I'm sure you will enjoy that too.

Matt Pulzer
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Program that!

Techno Talk

Max the Magnificent

With the introduction of the latest programmable devices, I think we've finally reached my WTW ('what the what') moment. I'm going back to playing with 8-bit microprocessors. It's time for younger engineers to take the strain. Good luck!

Over the course of my career, I've met many engineers who have experienced problems adapting to new technologies. For example, people who were experts designing circuits using valves (vacuum tubes) but who simply couldn't wrap their brains around circuits based on transistors.

I can understand this because I have the same problem the other way round – that is, I have no problem deciphering or designing a transistor-based circuit, but a tube-based schematic conveys as much information to my brain as would a wall of ancient Egyptian hieroglyphics.

What I found harder to comprehend was older engineers who had blackbelts when it came to designing digital logic with transistors, but who found the concept of digital integrated circuits (ICs) – even jellybean logic like 7400-series TTL and 4000-series CMOS – to be beyond their comprehension.

I wonder if anything like this will one day happen to me. Will a new technology arise in my lifetime that causes me to say WTW ('what the what')?

Now that think about it, I have seen the origination and evolution of one such technology – that of programmable logic. I remember the early days with nostalgia (which isn't what it used to be).

The first PLDs

When ICs like the 7400-series first appeared on the market in the mid-1960s, they took the world of digital design by storm. The only downside was that any functions they contained were 'frozen in silicon,' as it were. What was required was a device that could be purchased off-the-shelf and then configured (programmed) by digital design engineers to implement custom functions as required.

Early programmable ICs first appeared in the early 1970s. These were generically referred to as programmable logic devices (PLDs). The first PLDs were programmable read-only memories (PROMs), which can be visualised as a fixed array of AND functions driving a programmable array of OR functions. These were followed in 1975 by programmable logic arrays (PLAs), in which both the AND and OR arrays could be programmed. In turn, the late 1970s saw the introduction of programable array logic (PAL) devices in which the AND array was programmable while the OR array was fixed.

PLDs enjoyed a variety of programming technologies. For 'antifuse', desired connections could be selectively added ('grown'). By comparison, for 'fusible links', unwanted connections could be removed ('blown'). In both cases, this was achieved by applying higher-than-usual voltages and currents to the device's pins.

When designing printed circuit boards (PCBs), we used PLDs for all sorts of things, including implementing look-up tables, creating simple finite state machines (FSMs), and gathering a lot of 'glue logic' functions into a single device. We also included them in the design to provide a way to fix unforeseen board-level problems – it was a lot easier to swap out a socketed PLD than it was to cut tracks and add components and patch wires to the main board.

The 'Dark Ages' of design tools

It's hard for young engineers to understand how little we used to have in the way of design tools. For PLDs, we captured the desired functionality using pencil and paper, either as truth tables or schematics for logical functions, state diagrams for state machines, or tabular representations for look-up tables.

Next, we hand-created a text programming file, which required knowledge of the device manufacturer's proprietary file format and an intimate understanding of the device's internal architecture. Then we used this text file in conjunction with a manufacturer-specific programming device to configure the device as required.

It wasn't until the early 1980s that industry standard file formats and programming tools started to appear on the scene. I'm thinking of things like the file format proposed by the Joint Electron Tube Engineering Council (JETEC), as was, along with names like PAL Assembler (PALASM), Advanced Boolean Expression Language (ABEL), Common Universal Tool for Programmable Logic (CUPL), and – my favorite – Automated Map and Zap of Equations (AMAZE).

The first FPGAs

The company Xilinx was founded in 1984. A year later it introduced the first field-programmable gate array (FPGA). I think of the programmable fabric in FPGAs as little 'islands' of configurable logic in a 'sea' of configurable interconnect. The first of these devices was the XC2064, which contained an 8x8 = 64 array of configurable logic blocks, each boasting two 3-input lookup tables (LUTs).

The configuration was implemented using SRAM cells, which required loading from an external source when the board was powered up. Once again, this predated any FPGA-specific programming tools, so the configuration had to be captured as a text file by hand.

'Well, these devices will never catch on,' I remember thinking to myself, thereby proving I'm no clairvoyant (although I'm sure I could play one on TV).

And then it was now

As well as a bunch of smaller players, there are two FPGA behemoths in the industry – Altera (founded in 1983, purchased by Intel in 2015, and spun off as a wholly-owned Intel subsidiary in early 2024) and Xilinx (which was acquired by AMD in 2022). Over the past 40 years, this duo has evolved FPGAs and their design tools beyond all expectation and – in my case – comprehension. For example, AMD recently announced their Versal AI Edge Series Gen 2 SoC FPGAs for artificial intelligence (AI)-driven embedded systems at 'the edge' (ie, where the internet meets the real world).

In addition to millions of look-up tables, the programmable fabric includes thousands of digital signal processing (DSP) functions and megabits of Block RAM functions. Also, in addition to a bunch of artificial intelligence (AI) engines, there are eight 64-bit Arm Cortex-A78AE Application Processors and ten 32-bit Arm Cortex-R52 real-time processors, plus external memory and communications interfaces, all implemented on a single monolithic silicon chip.

I think we've reached my WTW moment. I'm going back to playing with 8-bit microprocessors. It's time for younger engineers to take the strain. Good luck!

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Practical Electronics is offering its readers the chance to win a Microchip Curiosity HPC Development Board (DM164136) – and even if you don't win, receive a 15%-off voucher, plus free shipping for one of these products.

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Worth $61.99 (approx £48.99) each

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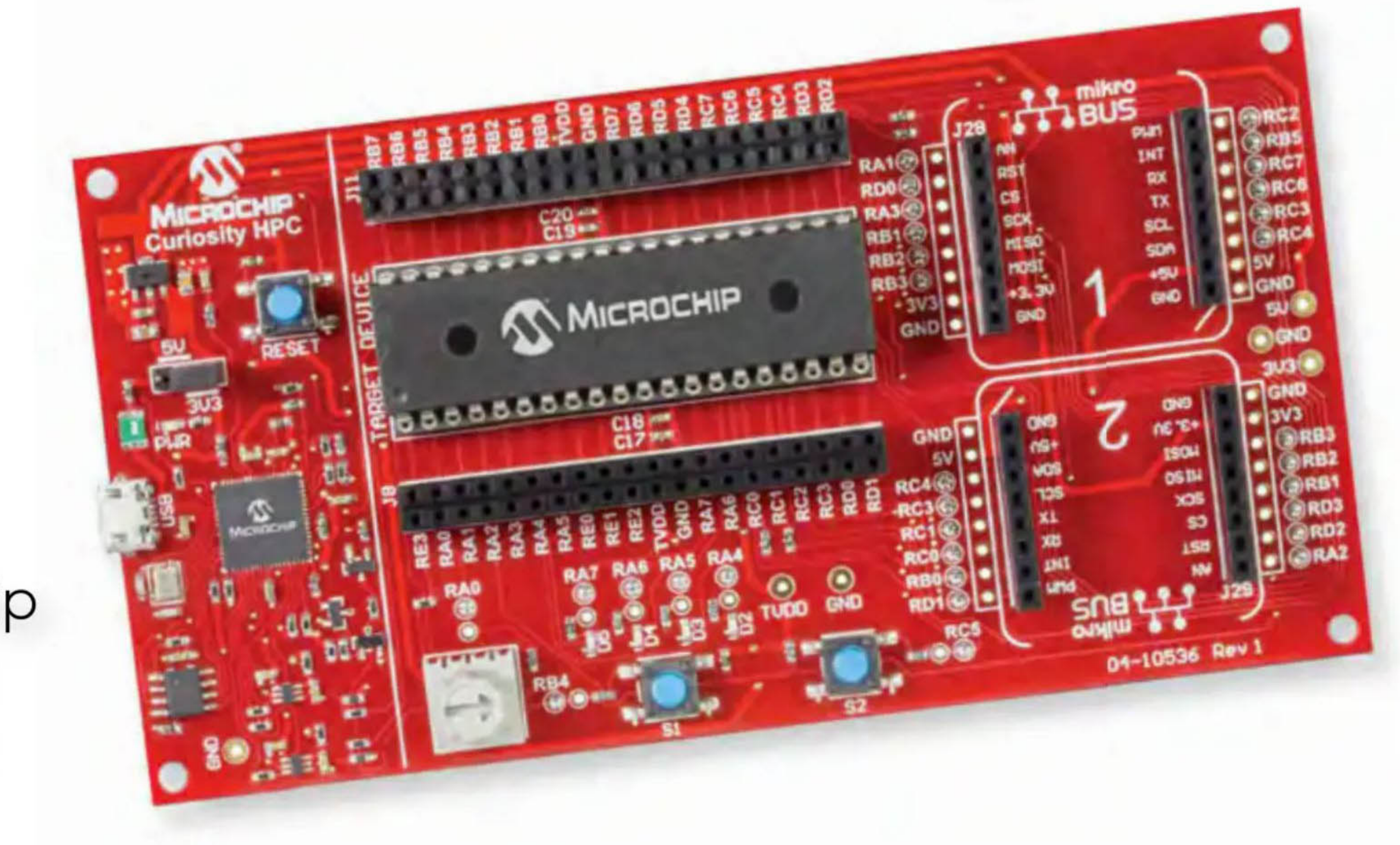

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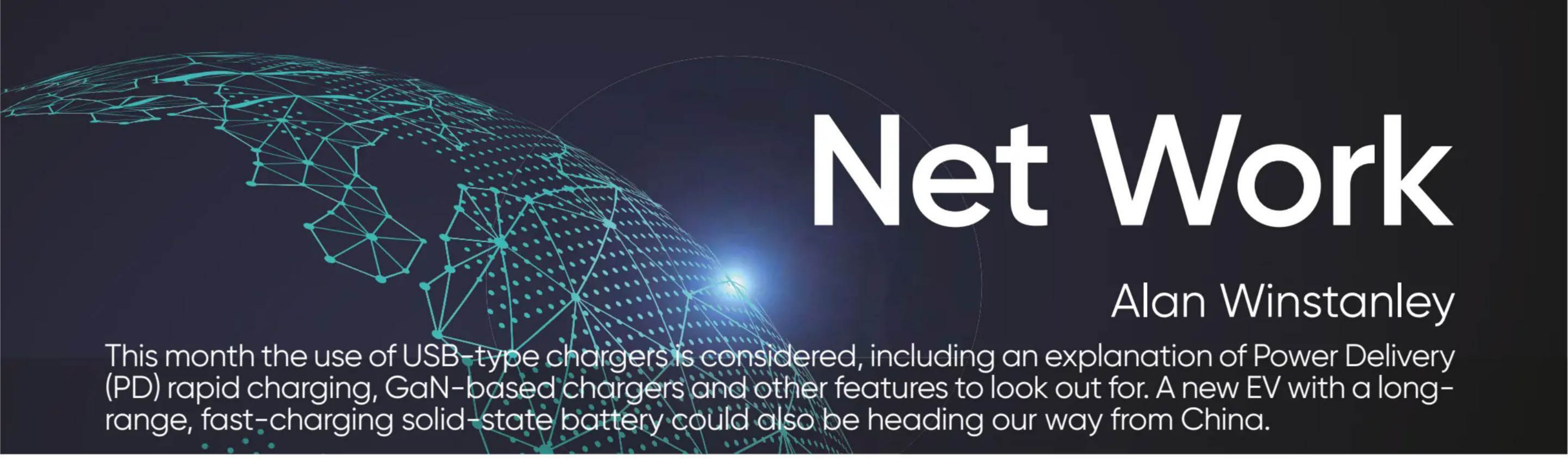


Net Work

Alan Winstanley

This month the use of USB-type chargers is considered, including an explanation of Power Delivery (PD) rapid charging, GaN-based chargers and other features to look out for. A new EV with a long-range, fast-charging solid-state battery could also be heading our way from China.

It's now almost 30 years since the universal serial bus first appeared in home desktop computers. The computer industry's launch of USB in 1996 brought with it the prospect of Windows 'plug and play' that would dispense with bothersome and bulky serial and parallel ports, supposedly making it easy for home computer users to install peripherals without needing expert computer knowledge. That was the theory, anyway.

Early USB technology also heralded a new simplicity in connecting devices to a PC. Computer users welcomed slender new USB 1.1 leads and they liked the idea that USB devices were hot-swappable, with no need to power down and re-boot a PC. As product design evolved, USB leads also provided a 5V power source for smaller peripherals, eliminating the need for separate mains adaptors.

The ubiquitous 'flat-style' USB A-type plug would eventually appear in all manner of consumer electronics, not just personal computers. Inevitably, higher speeds and miniaturisation saw smaller USB connector types introduced that we've all become familiar with. The original boxy-shaped B-type plug was soon superseded by the USB Mini, Micro and finally the rounded-rectangle USB-C type connector that is in widespread use today. A typical USB A-type to USB-C charger lead is shown below.

The traditional 5V USB A-type socket still appears on many mains chargers, and they power everything from rechargeable lanterns to Bluetooth speakers, ear buds, portable radios and handheld vacuum cleaners. Currently, rechargeable devices mostly use a USB-C type port for charging up, though the older USB Micro jack still puts in an appearance. At one time, a USB mains adaptor was bundled with mobile phones and tablets and inevitably we finished up with spare ones knocking around, prime candidates for the e-waste recycling bin. Now, mains adaptors are gradually being omitted as makers assume we already own one. Apple had previously gone its own way, as would be expected, introducing the 'Lightning' connector for the iPhone but, to reduce electronic waste, the EU has ordered Apple to change to the now universally adopted USB-C port by the end of 2024.

A typical high power USB charging lead showing A-type and USB-C plugs.

You can bank on it

Apart from using mains adaptors for charging, a glut of powerbanks is now widely available; rechargeable batteries that are very handy for on-the-go charging or for powering devices in inaccessible locations. Some gadgets now double as powerbanks themselves, offering a USB A-type or C-type port (or both) to charge a cellphone or other gizmo. I have an LED lantern and even USB hand warmers that do this. With Chinese manufacturers awash with Li-ion batteries and LEDs, the camping light shown above right is typical of what's on offer today – apart from containing an LED spotlight, a dimmable LED work light and a red flashing beacon, an A-type port provides a powerbank function, and an LED battery level meter is thrown in for good measure. Having to cycle the power buttons repeatedly to reach the desired function is a nuisance, but it's hard to know how much more tech they can cram into it for the money. A palm-sized dome light, also shown, offers a spotlight, a warm and cool white light, a flashing red beacon, LED level meter, magnetic mounts and hooks, and a USB 5200mAh powerbank.

Some USB chargers offer almost every power port ever made, and it starts to get a bit much when a powerbank bristles with USB A-type, USB Micro, USB-C and iPhone Lightning ports for good measure. Things get more complicated still when you learn that many USB-C ports can now act both as power inputs (for charging up powerbanks) and outputs (to power other devices) – the 20,000mAh power bank shown opposite has a mystery USB-C on the side offering high-power *bidirectional* charging, but you'd never know without checking the user manual.

This rechargeable LED camping lantern isn't short of features, including an A-type powerbank outlet. It has a built-in A-type USB lead for recharging.

Some present-day users express disbelief that A-type ports still even exist, because they use end-to-end USB-C types on their devices and chargers. It's possible that legacy A-type ports will gradually be replaced with USB-C connectors, especially as higher power products come to market, but for most people there's plenty of life left in the old A-type port.

While we're talking about USB, here's a reminder about USB data transmission rates themselves: legacy blue-colour USB ports are USB 3.0 (5 Gbps) or 3.1 (sometimes marked SS or SS10 – Superspeed 10 Gbps), while ports marked SS20 or Superspeed 20 can operate up to 20 Gbps. The colour of the plastic substrate found inside USB A-type ports

This palm-size camping light also has a USB A-type powerbank port.

The non-descript USB-C port on the side of this 20,000mAh powerbank provides bidirectional rapid charging.

is fast becoming irrelevant – instead of blue, each one on my laptop is black! The latest USB 4 standard sees data transfer rates of up to 40 Gbps and, looking ahead, readers can expect to see all manner of confusion arising from the use of USB-C and USB 4 cables. As computer manufacturer Lenovo reminds us, they are not interchangeable, and you can read more on this at: **https://bit.ly/pe-jun24-len**

Express power delivery

Still on the theme of USB-type power supplies, users of modern smartphones and laptops increasingly focus on a charger's wattage and the time taken to recharge. Mains chargers with power ratings approaching 100W or more are marketed, though, judging by Amazon's range, 30-40W chargers are more likely a cost-effective choice for many mobile users at the moment. Laptop users need even higher ratings, with up to 240W becoming available as new technical standards are agreed, remembering that these utilise USB-C type connectors instead of the clunky DC power jacks we've used for decades (as shown in *Net Work*, September 2023).

FAST CHARGE 3.1A
HUAWEI

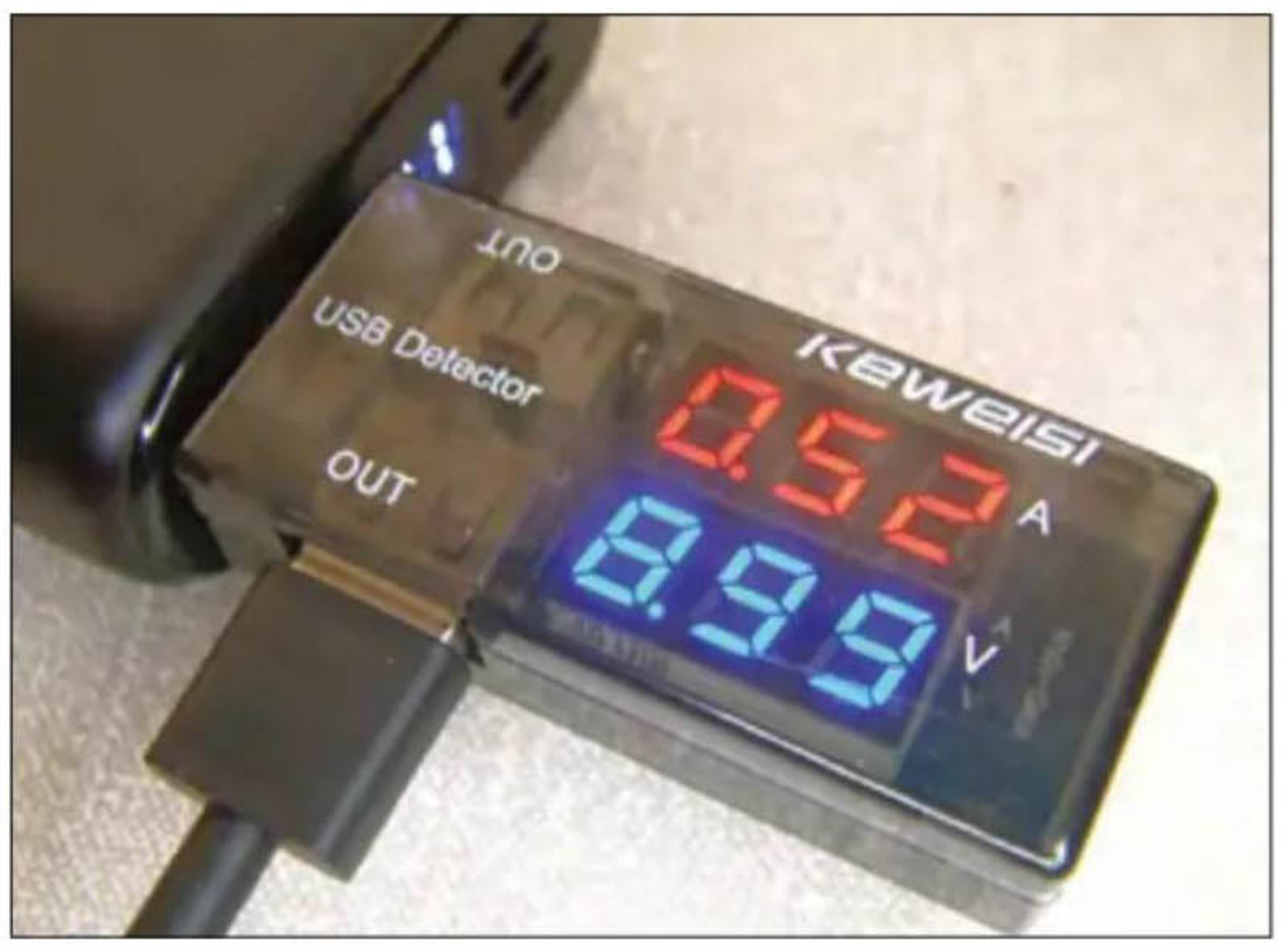
This neat USB charging lead is rated at 3.1A and has an LED indicator.

USB Charger
Max. 5V DC 5100mA

USB charging ports are increasingly found on domestic mains wall outlets. (**Seeswitches.co.uk**)

A basic 'dumb' 5V switched-mode supply might be limited to, say, 2A or less, but using them to charge modern high-power devices can take an inordinately long time.

USB chargers rated at 5V, 2-2.4A ($P = IV$, so 10-12W) also find their way into 13A mains wall outlets and power strips. Basic 5V A-type ports even appear in bedside lights, offering overnight phone charging. I use silicone rubber port covers, available from AliExpress for next to nothing, to stop debris falling in or shorting out the USB outlet.



USB monitor on an A-Type powerbank port showing 'PD' in action – 9V from a USB port.

A 'dumb' 5V charger built into a touch-operated bedside light. Silicone rubber dust covers are a good idea, available separately.

To meet the need for faster charging times and higher power, intelligent electronics is used to overcome the limitations of the legacy 5V rail, which originally only supplied up to a couple of watts for 5V plug-and-play devices. Power delivery (PD) standards offer fast charging through a USB-C port, as PD-compatible products can interact to raise the voltage and current, thereby reducing the charging time. Spec sheets show how a typical PD power

This tiny USB-C inline monitor fits a USB-C plug so you can keep an eye on charging progress.

Shown in use charging a smartphone, with power and PD displayed.

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UGREEN
USB-C

This Ugreen USB PD-compatible charger uses GaN semiconductors for compact size and greater efficiency. It has a USB-C port and the mains pins fold flat for portability.

charger can offer 5V, 9V, 12V and maybe 15V and 20V output voltages, all from a single USB port. With power levels exceeding 100W and even reaching 240W, uprated USB cables with appropriate current ratings become necessary to get the most from the system. Some fast-charge leads even have a built-in LED.

The technicalities of power delivery are beyond the scope of this column, but PD can be observed in action using digital monitors that are cheaply available online. A larger USB monitor is shown in the photo on the previous page that fits an A-type socket and displays the output on 7-segment displays. No longer is a USB rail clamped at 5V – by connecting my smartphone to a PD-compatible powerbank, I saw the 5V supply rail jump to 9V at nearly 1.5A before settling down until charging was complete. A typical smartphone can be fully charged in 90 minutes or less, this way.

Suppliers such as AliExpress offer scores of USB monitors and higher power connecting leads, which can be handy for checking a device's charging status at a glance. The photos above also show a tiny add-on USB-C inline monitor against a 50p piece for size comparison, which shows wattage and a 'PD' icon when charging a phone and power delivery is operating. These cost just a few pounds from Temu or AliExpress.

A detailed summary of USB PD protocols can be found on Wikipedia at: **https://bit.ly/pe-jun24-usb**

Quick Charge or 'QC' is an alternative fast-charging protocol used on some devices, and other proprietary systems are also available. With so many factors to think about, it's easy to see the appeal of wireless charging instead of grappling with fragile cables, and these contactless charging pads are increasingly commonplace at home and in the car.

GaN is the answer

The latest crop of mains chargers now caters for fast charging, and I was attracted to a compact 'Nexode Mini 30W' (maximum) type made by Ugreen. It has fold-away mains pins – a good idea when travelling – and the specification is typical of rapid chargers, switching intelligently between 5V, 9V, 15V and 20V and supporting PD3.0, QC3 and other protocols. This entry-level model costs just £13, however it only has a single USB-C port. A suitably rated good-quality USB cable should be used. It feels solid and well made, and unlike many anonymous imported types I was pleased to see a proper EU Certificate of Conformity included, so everything seems traceable as it should be. Another Ugreen model has both an A-type and USB C-type port, and other versions rated up to 160W are sold, priced at about £100.

This compactness of this charger is down to the use of GaN (gallium nitride) power semiconductors rather than silicon. It's claimed that GaN is as reliable as silicon, and as GaN is more efficient and can operate at higher temperatures, a greater power density means less heatsinking and cooling are needed, so a smaller but more powerful charger can be manufactured. When choosing a mains charger, a GaN type would make a good choice today and would likely be future proof too.

GaN semiconductors are most often used in industrial power electronics, and more background can be found on the Texas Instruments website at: **https://bit.ly/pe-jun24-gn**

The physics and merits of GaN power devices themselves are detailed in an academic paper, *GaN-based power device: physics, reliability and perspectives* hosted on the HAL (*Hyper Articles en Ligne*) Open Science website at: **https://bit.ly/pe-jun24-hal**

The direction of travel

Depending on one's lifestyle, there's no doubt that electric vehicles are the perfect solution for some motorists, but their impracticalities and drawbacks are well known. It's been suggested that more British motorists, deterred by the huge list prices, will likely sign up to car dealer subscription plans (or 'renting them' as it's also called), instead of buying outright and risking huge depreciation and repair bills afterwards.

A Chinese database tells me that nearly 400 (four hundred) different battery electric vehicles and about 170 hybrids are on sale there. Some of them are plain wacky or weird microcars and, happily, most will stay put in China where sales of EVs and NEVs (tiny Neighbourhood Electric Vehicles) have gone through the roof. Even smartphone makers are getting in on the act: Xiaomi has just launched the $30-42,000 SU7 luxury sedan range – call it up at: **https://bit.ly/pe-jun24-mi**

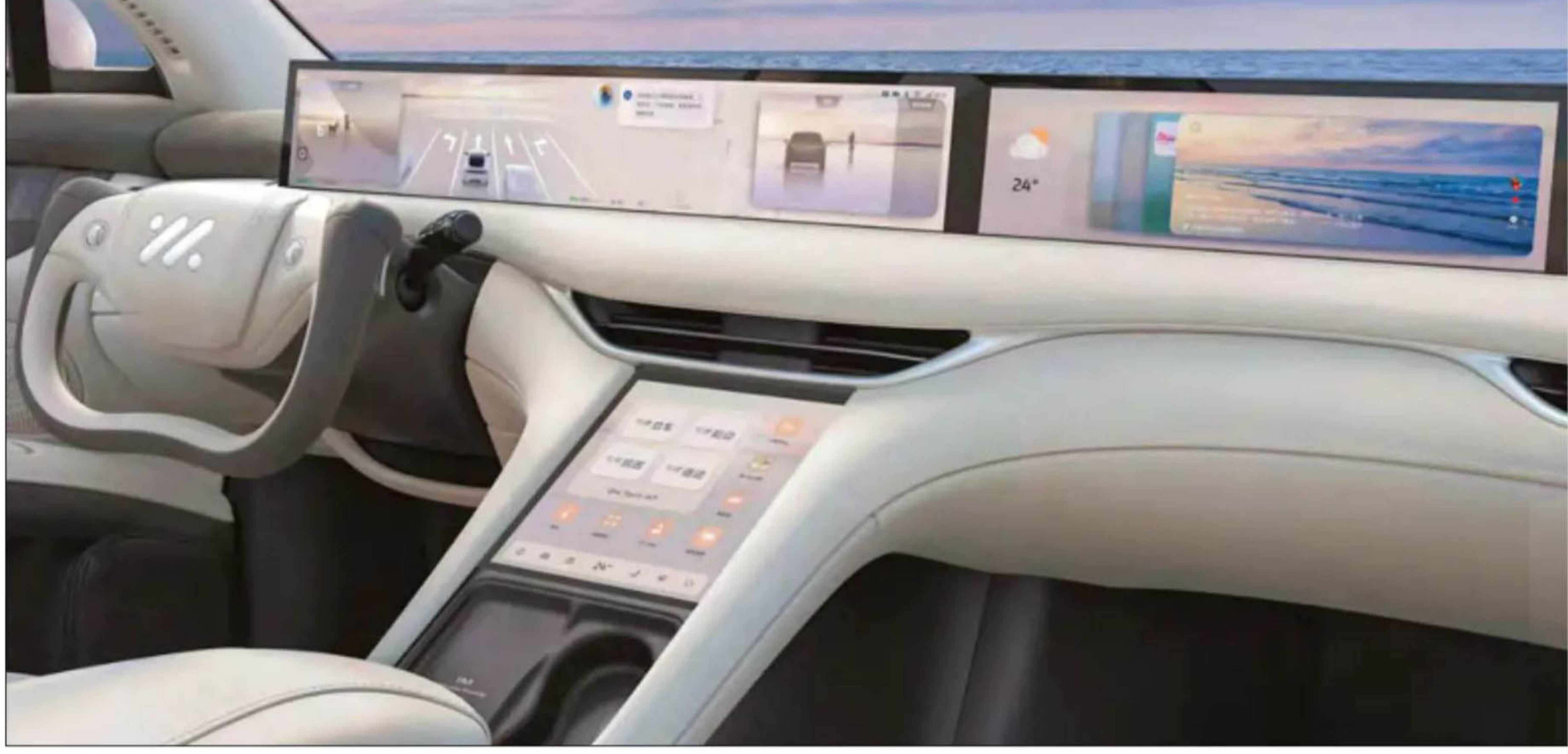
BYD – Build Your Dreams – produces some thirty EV models according to the database, selling three million last year in China alone. In mainland Europe, the EV market faces uncertain times as private buyers shun costly EVs and hang on to their petrol and hybrids cars. As the market evolves, major brands like BYD will slug it out with Tesla for market share, perhaps with US import tariffs imposed to throttle sales of Chinese EVs in America.

Some EV brands mentioned in previous columns have since fallen on hard times. Highly regarded Polestar is losing Volvo's financial backing and Geely (who also own Volvo) will take over. In the May 2022 issue, I described Fisker's green, recycled electric SUV credentials – so far in 2024, Fisker has sold just 207 cars in the UK. (BYD sold 1,278, about the same number as Polestar, but Tesla sold nearly ten times more, 11,768.) According to *Fleet News*, Fisker is slashing prices by £14,000 to shift unsold stocks, but buyers will have to accept that Fisker's after-sales service, support and warranty claims will be severely restricted. This is symptomatic of the turmoil facing the EV sector: I'm reminded of DeLorean's failed efforts to build a futuristic car in 1980s Northern Ireland, but we've seen nothing yet, as more new brands and developments are coming over the horizon.

Solid-state Survivor

An emerging Chinese brand, IM Motors, (Innovation in Motion) is an EV joint venture created to beat Tesla head on, and it's launched a market first: the IM L6 is a mid-size saloon that they claim

A teaser shot of the first EV mass produced with a solid-state battery. The mid-size IM L6 saloon may be exported under the MG brand, sources say.



The IM L6 interior has an expanse of three screens; early PR shots suggest its steering wheel is more like a yoke or control column.

is powered by the first mass-produced, ultra-fast charging ternary lithium NMC (nickel-cobalt-manganate) battery. The solid-electrolyte battery promises greater safety and a far longer range, along with very fast charging times. The same battery platform may also be licensed to Audi for forthcoming new EVs, and one can also expect to see much rivalry with BYD's 'blade' battery. However, there's a big 'gotcha' to be wary of: while ranges of up to 1,000km/ 600 miles are quoted, these are so-called CLTC values – China Light-Duty Vehicle Test Cycle figures. In other words, they are inflated over likely real-world ranges to make them look more appealing. An insightful YouTube video explains why CLTC figures should be treated with a large pinch of salt – see: **https://youtu.be/5s0CFAuQ4BM**

At the time of writing, IM's website has suddenly, and annoyingly, 404'd the English pages and images related to the L6, but I had managed to nab some on the Chinese section. The L6 has Tesla Y-like rear quarters and a futuristic-looking cockpit carrying full-width dash displays. The reason that this new model is significant, though, is that IM Motors is part-owned by SAIC (Shanghai Automotive), who also own the former British brand MG Cars, known for keenly priced EVs. When they reach our shores, IM's solid-state battery vehicles will reportedly be branded as mid-range MGs for sales in Europe and North America. If true, interesting times are ahead!

Power crazed

The UK has spent £13bn on a faltering smart meter programme to monitor electricity demand, with four million of them still not working properly, if at all. A smart meter fault-finding checker is listed at: **https://bit.ly/pe-jun24-chk**

Britain is also trying to swerve a looming energy crunch by building more gas-fired power stations, and proposals made by energy company RWE to build a new Combined Cycle Gas Turbine (CCGT) plant – one that reclaims 'waste' heat to drive a steam turbine and generate more electricity – would include piping waste carbon dioxide into abandoned undersea gas caverns, in a race to achieve 'net zero'. The plans won't be signed off by the Department for Energy Security and Net Zero (yes, there is such a thing) until the year 2027, RWE states. This means that the new power station is about half a decade away and new gas pipelines and transmission towers (pylons) will also be needed.

This stopgap measure wouldn't be so bad except that, in the same locality, 1.5GW of modern gas-fired power stations were bulldozed in recent years simply because they couldn't make any money. Appallingly, this included Killingholme 'A', a power station I adopted courtesy of National Power when the station was quite new, when researching my mini-series 'From Pipelines to Pylons' in the August and September 1999 issues of *Everyday Practical Electronics*. You can see the damage being inflicted on YouTube; note the larger 0.9GW neighbouring CCGT station lies demolished behind – see: **https://youtu.be/3k8SjEqVf0Q**

Until new energy sources such as SMRs (small modular reactors) come on stream, other measures may be needed to throttle demand and match it to the available supply pool. This may include 'surge pricing' or 'time of use' tariffs, effectively penalising users for consuming energy

Seen in happier times, Killingholme 'A' power station was built during the 1990s 'dash for [North Sea] gas' but demolished just 25 years later. (Photo: author)

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An artist's concept design of NASA's Lunar Terrain Vehicle. (Image: NASA).

at peak times. Disingenuous industry double-speak says that consumers will be able to celebrate 'saving money' by using energy off-peak instead.

There's no denying that smart meters and energy-saving measures are desirable and appreciated by many consumers, but I wrote some years ago that smart meters, themselves a market-controlling concept originating from within the EU, could ultimately be used as a tool against homeowners to influence their power usage. Paraphrasing Britain's Energy Saving Trust, that says the 'time of use pricing... adjusts the price of energy in real time, depending on demand. In homes, second generation SMETS2 smart meters automatically send updates to energy suppliers about household energy use at regular intervals.... so energy companies can see exactly how much energy its customers are using throughout the day, and would allow them to quickly adjust prices, according to demand.'

In theory, customer data could be uploaded wirelessly every 30 minutes, but often they transmit daily or even monthly instead. I think it's only a matter of time before the industry joins up some dots to match available renewable energy (wind, solar) against demand, and customers will then be penalised for turning on the cooker or electric heater on calm, cloudy, wintry days. But you could still turn everything off – think of all the money you'd save!

Other news

Amazon US is discontinuing its cashier-less 'Just Walk Out' shopping technology used in Amazon Fresh stores in America (see *Net Work*, May 2021). A very good insight into the amazing technology is presented at: **https://bit.ly/pe-jun24-amz**

An Amazon smart 'Dash' shopping cart – Amazon Fresh stores are dropping 'Just Walk Out' cashier-less AI technology in favour of smart shopping carts.

The tech uses advanced AI and weighing sensors to recognise and charge buyers when they add goods to their shopping basket, and when exiting the store their account is charged automatically, but many customers also wanted to see a rolling tally of their purchases and browse the store for offers, like the rest of us do. The stores are therefore being redesigned with smart 'Dash' shopping carts being introduced instead. Amazon has closed several UK retail stores, but the remainder will retain Just Walk Out for the time being. Attempts by rival supermarkets to use similar technology have not caught on and are never likely to, probably being better used in busy locations such as grab-and-go cafés, says *The Grocer* magazine. Amazon has also terminated by mutual agreement the acquisition of iRobot, makers of the Roomba robotic vacuum cleaner, blaming European regulatory problems.

NASA has short-listed three bidders tasked with designing the next-generation lunar terrain vehicle. The rover would be used by astronauts as part of the Artemis programme and will enable them to explore the South Pole and perform scientific experiments further afield than they could on foot. In between manned missions, the rover could be driven autonomously, with the winning contractor being allowed to perform commercial tasks, controlling the unmanned rover remotely from Earth. A movie trailer is offered by NASA at: **https://youtu.be/zTHJ9zb8J2s**

NASA has also been directed to devise a 'moon time zone' by 2026, called Co-ordinated Lunar Time (LTC). The White House order would establish a unified time standard at, and around, celestial bodies other than Earth, and NASA would work via standards bodies to establish LTC in conjunction with international agreements.

Last, this month, if you've ever needed data on legacy components such as old chips or transistors, or old computer software, one site worth keeping in mind is **bitsavers.org**, a resource containing 7.5 million pages of data maintained in an old-school file-area fashion for speed and ease of mirroring. One such mirror is hosted by the University of Kent, where archives of software, component data, test equipment and more will be found. There is even an FTP server for good measure – see: **https://bit.ly/pe-jun24-mir**

That's all for this month's *Net Work* – remember the above web links are ready-made for you to click on at our advert-free website at: **electronpublishing.com**

The author can be reached at:
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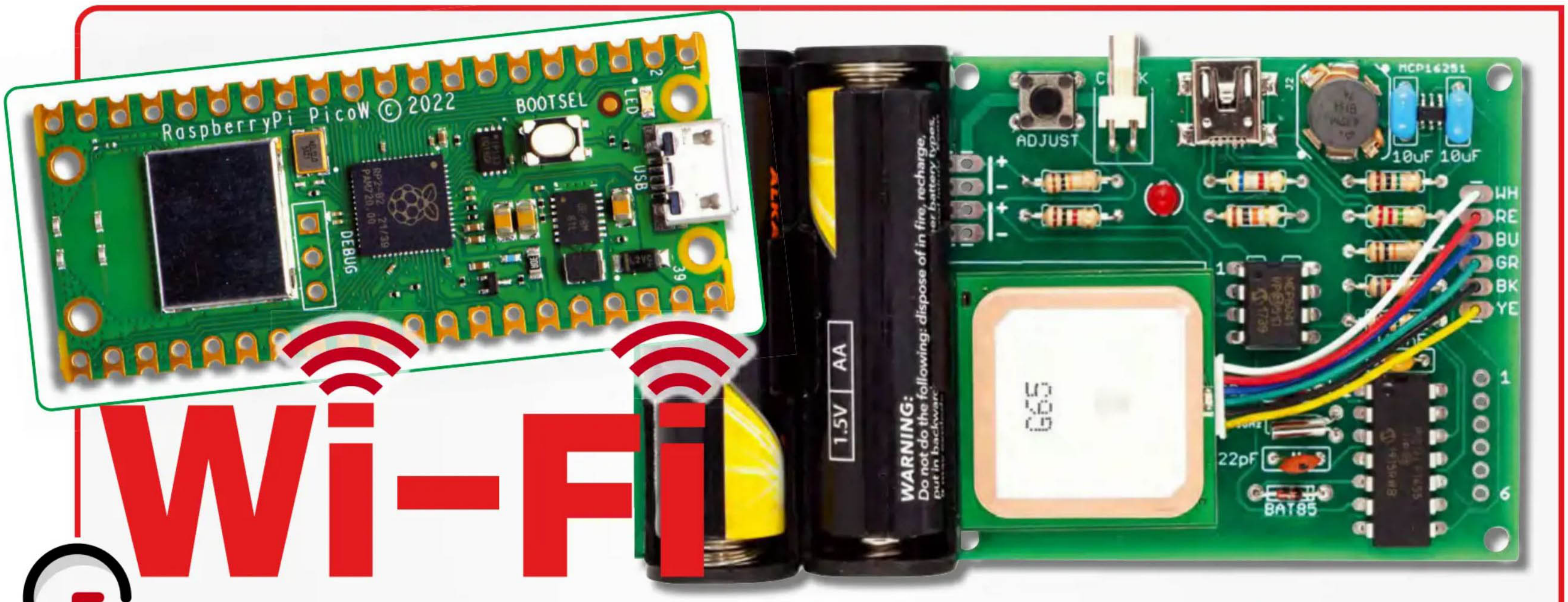


Wi-Fi Time Source for GPS Clocks

The Raspberry Pi Pico W can be used as a substitute for GPS modules in existing time keeping designs, for when you can't get a reliable GPS signal. It gets the time from an internet NTP server via Wi-Fi and is accurate to a fraction of a second.

Project by Tim Blythman

Ever since GPS modules have been affordable for the hobbyist, we have used them as accurate time sources. While GPS (and other similar satellite systems) has revolutionised navigation and mapping, it also provides easy global access to highly accurate time sources.

Each GPS satellite is equipped with two atomic clocks, and they transmit a very accurate time signal every second. We have used that signal for many projects to date, including the recent, very popular *GPS Analogue Clock Driver* from September 2023.

While GPS was the first GNSS (global navigation satellite system), there are now several more, including the Russian GLONASS, European Galileo and Chinese Beidou systems.

The Indian Regional Navigation Satellite System (IRNSS) and Japanese Quasi-Zenith Satellite System (QZSS) are designed to improve positioning on a national scale, with the QZSS also benefiting Australia as the satellites' orbits bring them over us.

While they use subtly differing technologies (even GPS has evolved over its 50-year existence), a common external interface has been established. In fact, the VK2828U7G5LF GPS module that we use for many projects can receive signals from GPS, GLONASS and Galileo satellites.

For the purposes of this article, we'll use GPS as an encompassing term for all the different navigation satellite systems. However, note that some of these systems are not truly global, as the satellites do not usually provide coverage at high latitudes (close to the poles).

Previous GPS Time Source

In the April 2019 issue of *PE*, we published the *Clayton's GPS Time Source*. As the name hints, it doesn't actually use any GPS technology, but rather it can be used as a source of GPS-like time signals when an actual GPS signal is unavailable. It's often recommended as a replacement for a GPS module in clock projects.

The motivation for this concept was driven by many clocks being used indoors, where very weak GPS signals are hard to receive. On the other hand, Wi-Fi signals are usually available indoors.

The actual hardware of the 2019 unit is simply a D1 Mini Wi-Fi ESP8266 microcontroller module. The module is programmed with firmware to connect to a Wi-Fi network and update an internal clock from the internet using NTP (network time protocol).

This time is then used to generate 'sentences' to communicate that time. A 1PPS signal is also generated, although this signal will not have the precision of an actual GPS module.

Pico W update

This project is an update of the original *Clayton's GPS* but using a Raspberry Pi Pico W instead of a D1 Mini. While we could have refactored the same code for the Pico W GPS, there are several reasons why we did not.

We have had many suggestions for improvements over the last five years, so it made sense to incorporate them where possible.

We've chosen to use the C SDK as we found that it gave us better access to low-level functions and programs run more quickly. Some of the new features were possible (and much easier to implement) due to aspects of the C SDK and its software libraries.

There is no doubt that the Pico W is very well priced, making it an attractive option when the module is all or most of the hardware required.

What projects does it work with?

New GPS-Synchronised Analogue Clock	Practical Electronics, September 2023
GPS-Synchronised Analogue Clock	Practical Electronics, February 2018
High-Visibility 6-Digit LED GPS Clock	Practical Electronics, January 2017 – February 2017
6-Digit GPS-Locked Clock	Practical Electronics, May – June 2011

Wi-Fi Time Source Features

- Delivers NMEA 0183 data simulating a GPS time source
- Adjustable baud rate
- 3.3V logic levels work with 3.3V and 5V systems
- Synthesised 1PPS signal
- Gets the time from NTP servers via Wi-Fi
- Generates estimated latitude and longitude based on IP address
- Can also output fixed dummy coordinates
- Can scan for up to eight Wi-Fi networks (SSIDs)
- Configurable via virtual USB serial port, independent of data stream
- Uses a compact and low-cost Raspberry Pi Pico W module
- Integrated buck/boost converter runs efficiently from 1.8-5.5V
- Crystal oscillator offers better than 30ppm accuracy between updates
- Draws 50mA, or up to 100mA during Wi-Fi transmissions (3.0V supply)

Indeed, it is cheaper than the GPS module it can replace. But particular features of its RP2040 microcontroller helped us to create the *Wi-Fi Time Source*.

For example, it can implement a virtual USB serial port, meaning that the configuration menu is separate from the NMEA data stream (National Marine Electronics Association). Due to the nature of the serial port on the D1 Mini, these were shared on the *Clayton's GPS*, so using the configuration menu interrupted the data stream.

The Pico W also implements a virtual USB drive for flash memory programming. Some people had difficulty uploading to the flash memory to the D1 Mini for various reasons. For example, it requires either a dedicated programming application or the Arduino IDE for programming.

On the other hand, the Pico W can be flashed by just about any computer with a USB port. The process is as simple as copying the file to the virtual USB drive.

The RP2040 processor on the Pico W has two cores, so one can be dedicated to sending out the NMEA data and not be blocked by activity on the other core, which handles the configuration and Wi-Fi connections.

The Pico W also has an onboard switchmode regulator that's more efficient than the linear regulator found on the D1 Mini. Some readers reported problems powering the D1 Mini, so it is a welcome upgrade. It not only reduces the current requirement at higher supply voltages but also enables operation from supplies as low as 1.8V.

Just like the earlier time source, the *Wi-Fi Time Source* emits three NMEA sentences: 'RMC' (recommended minimum data for GPS), 'GGA' (Fix information) and 'GSA' (satellite data).

Most of our GPS clock designs only use the RMC sentence, with some also using GGA. So this data is entirely adequate for driving those clocks.

NMEA sentences

Practically all GPS modules deliver data generally in accordance with the NMEA 0183 standard. The standard actually specifies 4800 baud serial data using a balanced signal complying with the RS-422 electrical standard.

The newer NMEA 2000 standard uses a CAN bus network at 250kiB per second. The full contents of this standard are not publicly available, so the simpler NMEA 0183 is still widely used, since it is well known and understood.

Most receivers nowadays use single-ended logic-level signals (typically 3.3V) with baud rates of 9600 or even higher. Many modules also offer a 1PPS (pulse per second) signal that is synchronised to the satellite atomic clocks.

The serial data consists of lines of ASCII characters called sentences. For our purposes, each sentence is marked at the start by a '$' character, followed by two characters that identify the 'talker'. This is typically 'GP' for GPS systems, although we have seen some modules that use 'GN' where data from multiple satellite systems are combined.

The next three characters identify the type of message, followed by sentence-specific data and a checksum code to provide a degree of protection against corrupted data.

The most common sentences that encode the time also contain location data, so the *Wi-Fi Time Source* can produce dummy location data or even use an IP address geolocation data service to generate an approximate location. In any case, it's a good idea to generate such data in case the receiving device expects there to be valid data in this location, even if it is not used.

This approximation will never be good enough for navigation purposes. Still, it is usually sufficient to determine a timezone, which is ideal for those clocks that use GPS location data for this purpose.

For example, the *High Visibility 6-Digit LED GPS Clock* from January and February 2017 uses location data to set the time zone and daylight savings rules automatically.

With most of our GPS projects using the GPS signal for clock timekeeping, the *Wi-Fi Time Source* is well-suited for use with indoor clocks, where they may not have a view of the sky and thus to a GPS signal, but can easily be connected to a Wi-Fi network.

Hardware

The *Wi-Fi Time Source* hardware is minimal. The dashed box in Fig.1 shows the pinout of the Pico W after it has been programmed. The remainder of Fig.1 shows the full map of all the pins with their features.

As you can see, we've kept all the useful pins at one end. It would have been nice to be able to shorten the board by cutting off unnecessary section. Unfortunately, the entire board is needed and it can't be made much smaller, especially as the Wi-Fi antenna is at the end opposite the USB connector.

The power pins are fixed on the right-hand side, near the USB connector. These are pin 40 (VBUS), pin 39 (VSYS) and pin 38 (GND). There are actually several GND pins (see Fig.1), but pins 3 and 38 are closest to the other important pins.

Pin 37 (3V3_EN) is an input to the regulator on the Pico W; this is kept high by a 100kΩ resistor but can be pulled low to shut down the regulator and thus power off the Pico W.

Pin 1 (GP0) is the source of the generated NMEA serial data, which idles at a 3.3V logic high level.

The Pico W's hardware UART (universal asynchronous receiver/transmitter) peripherals are only available on specific pins. This pin was chosen as it is the UART TX pin closest to the USB connector and the power pins. We selected the adjacent pin 2 (GP1) for the 1PPS output; it could have been any of the remaining GPIO pins.

We've shown the 3.3V output only because it might be handy if you need a regulated 3.3V supply for your project. The regulator on the Pico W can deliver up to 2A, although some of that is used by the Pico W.

Fig.2 shows the power circuitry of the Pico W and will help you decide how to connect the *Wi-Fi Time Source* in your circuit.

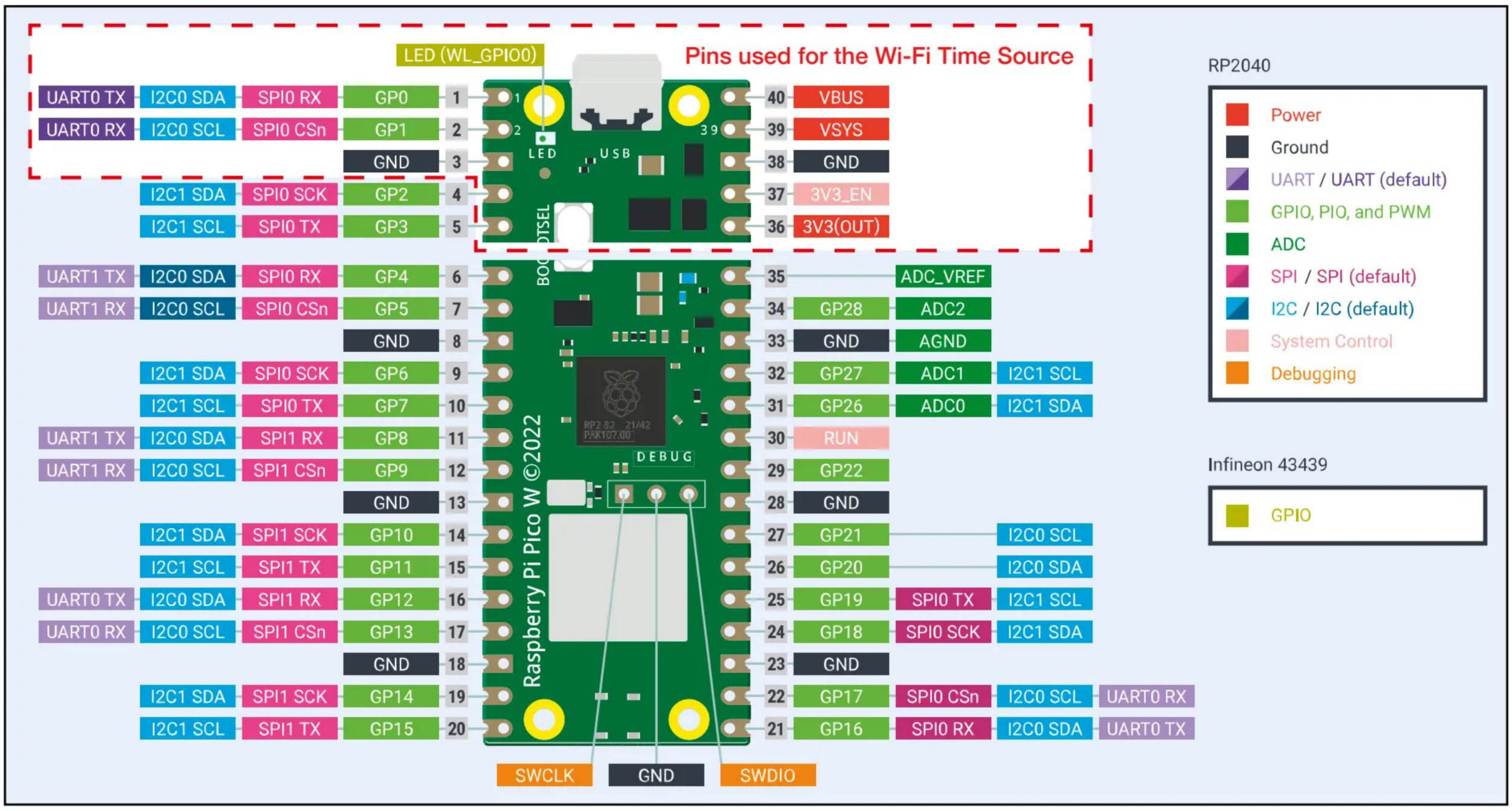

Pins used for the Wi-Fi Time Source
LED (WL_GPIO0)
UART0 TX | I2C0 SDA | SPI0 RX | GP0 | 1
UART0 RX | I2C0 SCL | SPI0 CSn | GP1 | 2
GND | 3
I2C1 SDA | SPI0 SCK | GP2 | 4
I2C1 SCL | SPI0 TX | GP3 | 5
UART1 TX | I2C0 SDA | SPI0 RX | GP4 | 6
UART1 RX | I2C0 SCL | SPI0 CSn | GP5 | 7
GND | 8
I2C1 SDA | SPI0 SCK | GP6 | 9
I2C1 SCL | SPI0 TX | GP7 | 10
UART1 TX | I2C0 SDA | SPI1 RX | GP8 | 11
UART1 RX | I2C0 SCL | SPI1 CSn | GP9 | 12
GND | 13
I2C1 SDA | SPI1 SCK | GP10 | 14
I2C1 SCL | SPI1 TX | GP11 | 15
UART0 TX | I2C0 SDA | SPI1 RX | GP12 | 16
UART0 RX | I2C0 SCL | SPI1 CSn | GP13 | 17
GND | 18
I2C1 SDA | SPI1 SCK | GP14 | 19
I2C1 SCL | SPI1 TX | GP15 | 20
40 | VBUS
39 | VSYS
38 | GND
37 | 3V3_EN
36 | 3V3(OUT)
35 | ADC_VREF
34 | GP28 | ADC2
33 | GND | AGND
32 | GP27 | ADC1 | I2C1 SCL
31 | GP26 | ADC0 | I2C1 SDA
30 | RUN
29 | GP22
28 | GND
27 | GP21 | I2C0 SCL
26 | GP20 | I2C0 SDA
25 | GP19 | SPI0 TX | I2C1 SCL
24 | GP18 | SPI0 SCK | I2C1 SDA
23 | GND
22 | GP17 | SPI0 CSn | I2C0 SCL | UART0 RX
21 | GP16 | SPI0 RX | I2C0 SDA | UART0 TX
SWCLK
GND
SWDIO
LED
USB
BOOTSEL
DEBUG
Raspberry Pi Pico W ©2022
RP2040
Power
Ground
UART / UART (default)
GPIO, PIO, and PWM
ADC
SPI / SPI (default)
I2C / I2C (default)
System Control
Debugging
Infineon 43439
GPIO

Fig.1: the pins on the Pico W that can be used for the Wi-Fi Time Source are shown in the dashed red box. Pin 1 (GP0) is the closest UART TX pin to the USB end of its PCB and is also near the relevant power pins. You probably won't need all the connections shown here for most clock projects (see Figs.3-6); three or four connections are often sufficient.
Pin 1: serial NMEA data; pin 2: 1PPS signal; pin 3: ground; pin 36: 3.3V; pin 37: 3.3V enable (active high); pin 38: ground; pin 39: 1.8V to 5.5V in; pin 40: USB supply.

Most people will simply need to connect a supply between the VSYS and GND pins. But note that there is a diode between VUSB and VSYS, so if a USB cable is connected, it might feed into VSYS, particularly if VSYS is less than the 5V from USB.

Unless you can be sure that you won't connect anything to VSYS while power is applied to VUSB (for example, via the USB socket), the safest option will be to connect the incoming supply to VSYS via a schottky diode, which will prevent current from passing from VBUS into your supply.

Given that most people will use the USB port to program, configure and test the Pico W, the easiest solution is to disconnect the USB cable before connecting to the target circuit. In that case, direct connections to the Pico W pins will be fine.

Later on, we'll also show you how to connect the *Wi-Fi Time Source* to some of our recent clocks.

Software development

The Raspberry Pi C SDK is still evolving, especially the parts of it that deal with the Wi-Fi features of the Pico W. But it is well documented, and interest is sufficient that the online community is also very helpful.

So, we ran into some minor difficulties during development, but we managed to work around them. We used version 1.5.0 of the SDK; versions before 1.4.0 did not support the Pico W and later versions might differ.

As we noted, the Pico W has two processor cores. One of these (the second core) is programmed to do nothing more than generate the NMEA data and 1PPS pulses. This is crucial as we found that the D1 Mini (as used in the 2019 *Time Source*) would occasionally block (be busy and not be able to run other parts of its program) during Wi-Fi operations.

By setting up one core to do the critical activity, the *Wi-Fi Time Source* can continue to operate, even in the extreme event that one of its processor core crashes entirely. This core can even reset the *Time Source* under some conditions.

When a reset happens, some data is stored in RAM to preserve the current time across the reset. This is possible as RAM remains powered during the soft reset process.

We saw very occasional crashes (and reset recovery) when the *Time Source* had been active for long periods, but this should not be an issue for operation with the recent GPS clocks, as the *Time Source* should only be powered long enough to set the time, after which it is powered off.

This second processor core looks at the current time and calculates what the time will be when the next second rolls over. It then prepares all its data to suit this next second. As soon as the second rolls over, the data is sent, and the 1PPS signal is pulsed.

This means that the NMEA data and 1PPS pulses are delivered with minimal jitter. Providing the output as the second rolls over means that the fractional data can be ignored, simplifying the code slightly, both for us and potentially for any device receiving that data.

The other core has the vital role of periodically getting an accurate value for the time and collecting the other data that is needed. One of these is a 'validity' flag, equivalent to the GPS 'satellite lock' that should always be checked to ensure that valid data is being received.

The Pico W implements an internal 64-bit counter with microsecond resolution. This counts up from zero when the processor starts or is reset. The documentation jokes that (in the vein of the Y2K or Millennium Bug) this will eventually cause a year 5851444 bug.

Such bugs typically occur when a counter rolls over beyond its maximum value. While we are not too concerned about this particular counter, it always pays to to be aware of these potential 'gotchas'.

The main role of the software running on the first core is to fetch an accurate timestamp from the NTP servers. This timestamp is compared with the current value of the 64-bit counter, and an offset is used

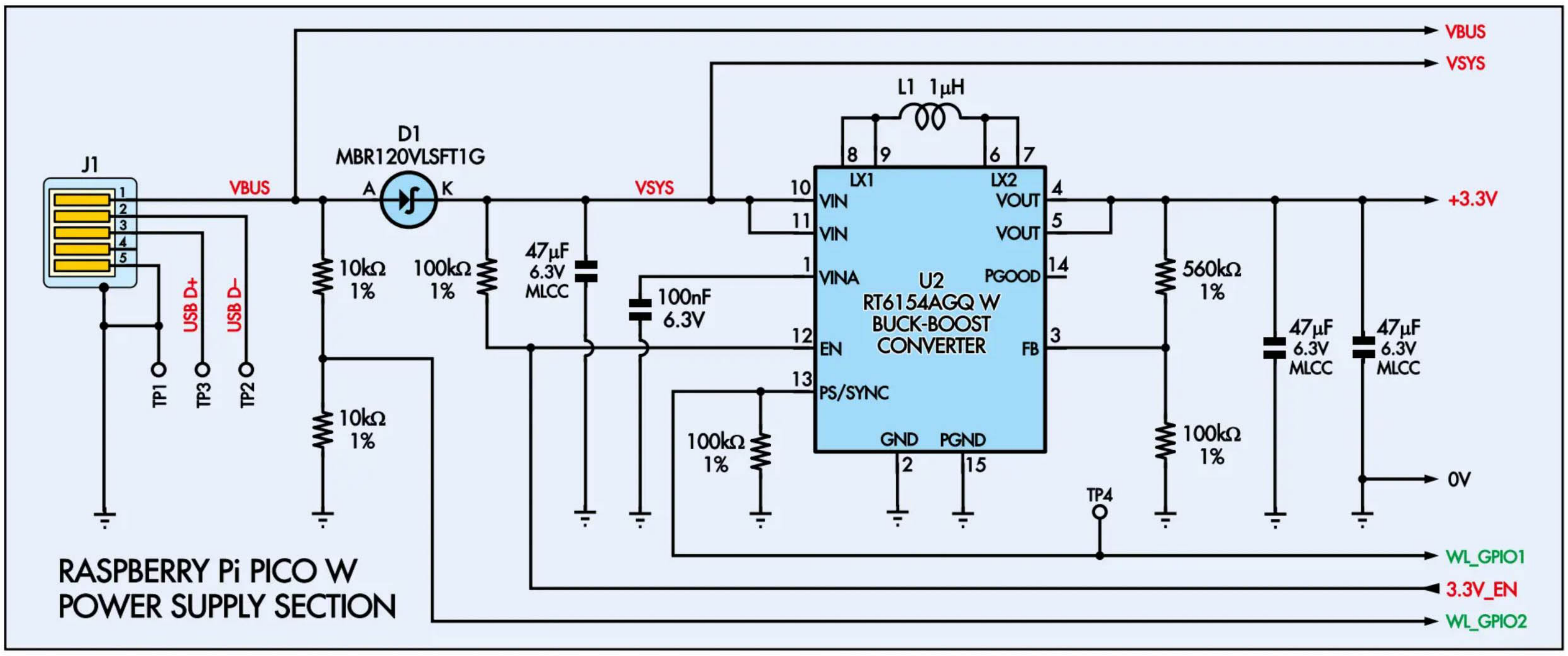


Fig.2: the power supply circuit of the Pico W, shown here in case you wish to adapt the Wi-Fi Time Source to a different application. For example, consider adding a diode feeding into VSYS to prevent VBUS power from feeding into your power supply if a USB cable is connected.

to calculate the actual time (at any time) by simply adding the current value of the 64-bit counter.

The RP2040 processor in the Pico W has an internal real-time clock peripheral, but this only has a resolution of one second, so we can't really use this to keep time accurately. However, we set it and use it in places where it is accurate enough, such as reporting time in human-readable form on the configuration interface.

The first core also provides a virtual USB serial port that is used to print an interactive menu with the help of a serial terminal program. This can be seen in Screen 1; we'll look more closely at the options later.

The menu allows up to eight SSIDs (Wi-Fi networks) to be set. The software will automatically cycle through these networks until it successfully connects to one. It will attempt to reconnect if the connection is lost.

Since many applications of the *Time Source* depend on it only being turned on briefly (to save draining battery power), the initial behaviour is to perform a network scan to ensure that the first attempted connection is to an available network.

The virtual serial port also produces status information, mainly concerning the Wi-Fi status and time since the last NTP update. One of the menu options allows the NMEA data to be dumped to the virtual serial port for easy debugging.

The first core is also responsible for controlling the Pico W's inbuilt LED, which is set up to flash useful status indications.

The LED is switched on solid when power is applied, indicating that the *Time Source* is powering up correctly. It can also flash once, twice or three times per second. One flash means it is connected to a Wi-Fi network, while two flashes indicate that the time is considered to be correct. Three flashes occur when both those conditions are true.

In general, the time is correct if an NTP update has been received in the last few hours, although this limit can be adjusted.

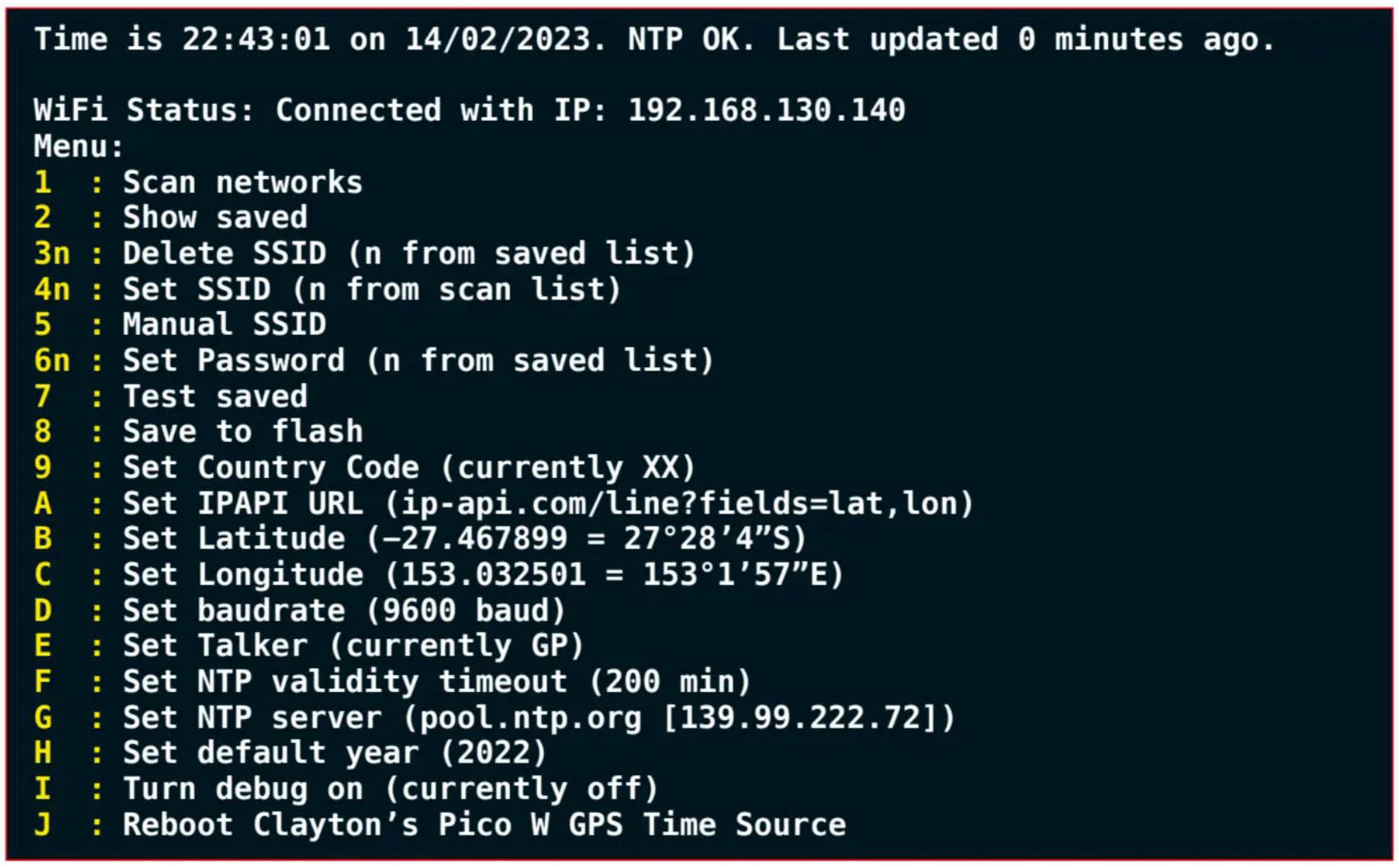
The crystal oscillator which is used on the Pico W has a 30ppm (parts per million) tolerance, meaning it could drift by up to one second every eight hours. However, in practice, we saw NTP adjustments up to 200ms, so we're confident that the time will be accurate within half a second with the default settings.

Programming the Pico W

It makes sense first to program the Pico W and check that it is working as expected. Hold the BOOTSEL button on the Pico W and plug it into your computer. A USB drive named 'RPI-RP2' should appear. Copy the **NEW_CLAYTONS_1.UF2** file to it; after a second or so, the LED should come on.

You can then use a serial monitor program to access the menu. We use TeraTerm on Windows, while minicom can be used on Linux systems. Open the Pico W's virtual serial port to access the interactive menu.

Ensure that your terminal program uses CR or CR+LF as its line ending. Since it is a virtual serial port, the baud rate is unimportant, and any baud rate setting should work.



```
Time is 22:43:01 on 14/02/2023. NTP OK. Last updated 0 minutes ago.

WiFi Status: Connected with IP: 192.168.130.140
Menu:
1  : Scan networks
2  : Show saved
3n : Delete SSID (n from saved list)
4n : Set SSID (n from scan list)
5  : Manual SSID
6n : Set Password (n from saved list)
7  : Test saved
8  : Save to flash
9  : Set Country Code (currently XX)
A  : Set IPAPI URL (ip-api.com/line?fields=lat,lon)
B  : Set Latitude (-27.467899 = 27°28'4"S)
C  : Set Longitude (153.032501 = 153°1'57"E)
D  : Set baudrate (9600 baud)
E  : Set Talker (currently GP)
F  : Set NTP validity timeout (200 min)
G  : Set NTP server (pool.ntp.org [139.99.222.72])
H  : Set default year (2022)
I  : Turn debug on (currently off)
J  : Reboot Clayton's Pico W GPS Time Source
```

Screen 1: many options are available to configure the Wi-Fi Time Source. At a minimum, you will probably need to use commands 1, 4, 7, 8 and 9 to set the country code and connect to your Wi-Fi networks to operate it with our GPS clocks. Other commands could come in handy depending on your application.

Table 1 – Wi-Fi Time Source configuration commands

Comm.	Function	Notes
1	Scan networks and display a list in order of decreasing RSSI	Channel and authentication are also listed. The number shown in column n is used for Command 4.
2	Show the current network list	The list is active but may not reflect the contents in flash memory unless a save has been completed.
3n	Delete item n from the list shown by Command 2	
4n	Add network n from Command 1	Also prompts for a password. If all slots are full, an error is printed and you will need to use Command 3 to free a slot.
5	Enter a network name manually	
6n	Enter the password for a network, using n from the list shown by Command 2	Shouldn't need to be used unless you need to change a password.
7	Test networks in the list	Scans through the list and attempts to connect to each network in turn. This can take a while and success is only reported if an IP address is obtained.
8	Save all settings to flash memory	It's a good idea to reboot after this to ensure that all settings are reloaded correctly.
9	Set two-letter country code	Only loaded on boot, so reboot after setting this and using Command 8 to save.
A	Set IP to lat/lon API URL	This should return two lines of text with decimal latitude on one line and longitude on the next. Set URL to blank to disable.
B	Set default latitude	Enter in the decimal format.
C	Set default longitude	Enter in the decimal format.
D	Set NMEA baud rate	The default is 9600, but any rate between 300 and 921600 can be used.
E	Set Talker code	The default is 'GP', but it can be any two characters. 'GP' works for all our clocks.
F	Set NTP validity timeout in minutes	The longest period for which the time can be considered valid without a (typically hourly) NTP update, from 60min to 50000min (about a month).
G	Set NTP server URL	The default is 'pool.ntp.org', which automatically redirects to a geographically nearby server. Others can be used, such as 'time.nist.gov'. The IP address may not be correct until a network is connected.
H	Set default year	The year used at boot when no other time data is available, from 1970 to 4095..
I	Toggle debugging NMEA data output to USB serial port	Can be used to check and debug the NMEA data. This setting is saved in case you need this data to always be available on the USB serial port.
J	Reboot Pico W	It's recommended to reboot after saving settings to ensure that all settings are reloaded at boot time. If you hold the BOOTSEL button while rebooting, you can use this method to enter bootloader mode.

Basic setup

All commands should be followed by Enter. The Pico W implements country codes to ensure that the correct (legal) Wi-Fi channels are used for communication. The default 'XX' setting is a subset that is safe worldwide but does not allow the use of some Wi-Fi channels. So it should work but might not be optimal.

It's a good idea to set this to your country. Use command 9 (followed by Enter) and enter a two-letter country code (AU, NZ, US, UK... and so on), then save the settings with command 8 and reboot the Pico W with the J command.

Editor's note: the codes should be in the alpha-2 format, see: **https://w.wiki/4kP**

Reconnect to the Pico W if necessary; TeraTerm will usually perform this automatically.

Now use menu option 1 to run a Wi-Fi scan; this should complete within a second or so. The networks are listed in order of RSSI (signal strength), so you should find your SSID near the top.

Note that commands listed with an n suffix take a second numeric argument. For example, if your network appears first (next to number 0), enter command 40. You will then be prompted for the password for this network; type it in and press Enter.

You can enter multiple networks without rescanning. If your network doesn't appear, use command 5 to enter the name manually, and you will then be prompted for the password too.

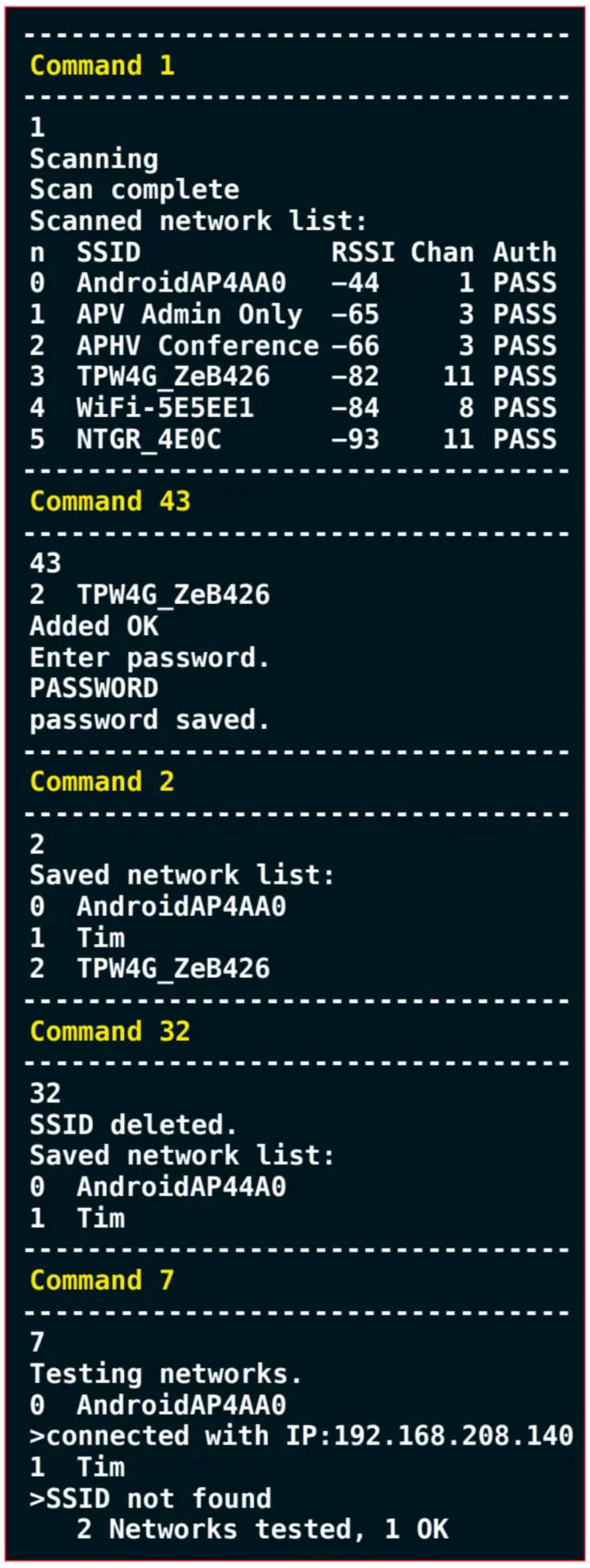
Command 6 on its own is used to change or set a password if, for example, you have entered it incorrectly.

Then try command 7 to test the saved networks. You should see a message saying 'Connected with IP', followed by an IP address for each SSID. If not, try again. If you get an 'Auth failed (password?)' message, the password entered may not be correct; you can use command 6 to re-enter it.

The serial port will print updates around every 15 seconds if nothing has been entered on the serial port – this is done to prevent any updates from interfering with your configuration process.

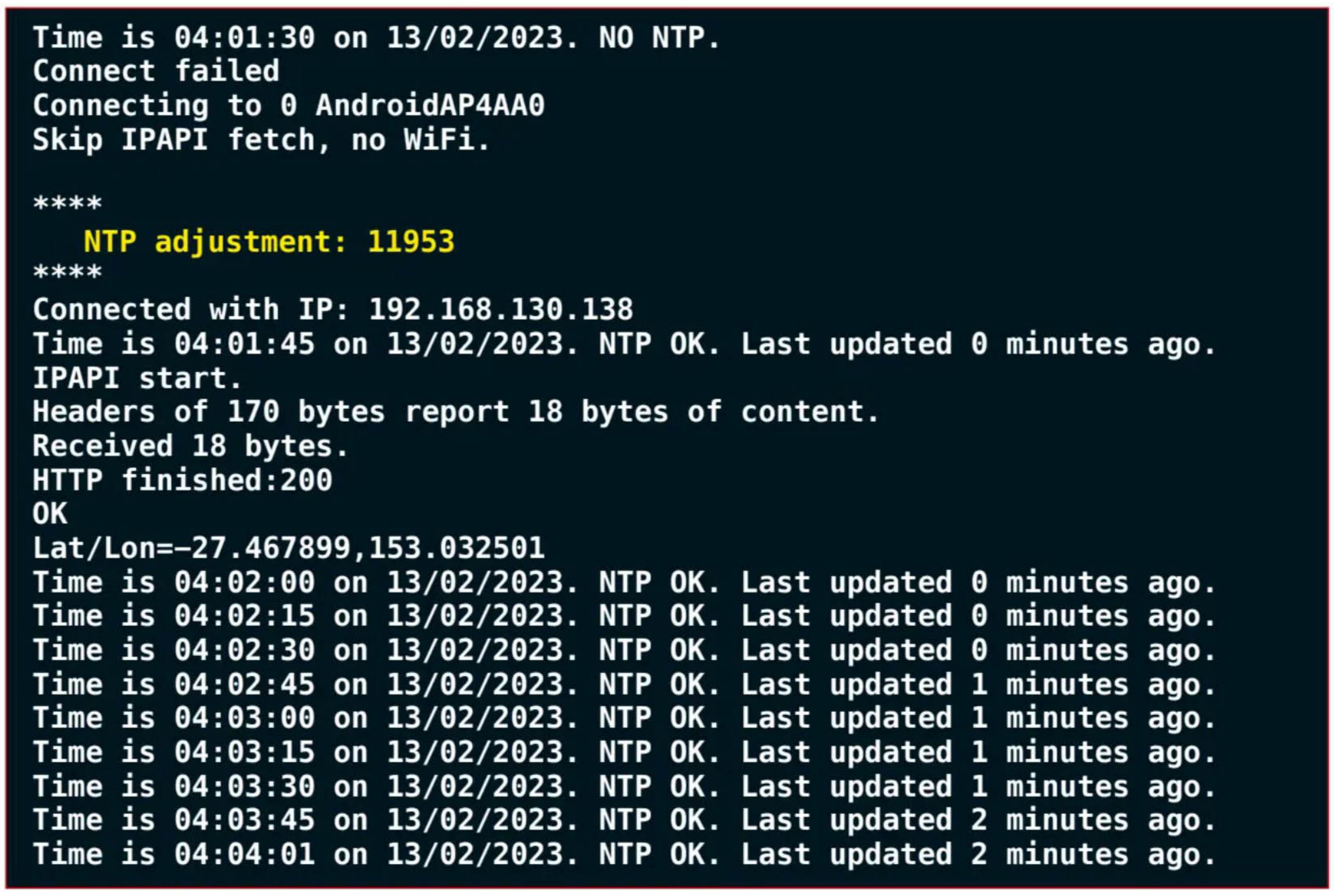
If all is well, use command 8 to save the settings to flash and reboot again to ensure that the settings are loaded. This is necessary as some parameters can only be set once, and the easiest way around this is to reboot the device.

This should be the minimal amount needed to set up the *Wi-Fi*



```
-----------------------------------
Command 1
-----------------------------------
1
Scanning
Scan complete
Scanned network list:
n  SSID            RSSI Chan Auth
0  AndroidAP4AA0   -44     1 PASS
1  APV Admin Only  -65     3 PASS
2  APHV Conference -66     3 PASS
3  TPW4G_ZeB426    -82    11 PASS
4  WiFi-5E5EE1     -84     8 PASS
5  NTGR_4E0C       -93    11 PASS
-----------------------------------
Command 43
-----------------------------------
43
2  TPW4G_ZeB426
Added OK
Enter password.
PASSWORD
password saved.
-----------------------------------
Command 2
-----------------------------------
2
Saved network list:
0  AndroidAP4AA0
1  Tim
2  TPW4G_ZeB426
-----------------------------------
Command 32
-----------------------------------
32
SSID deleted.
Saved network list:
0  AndroidAP44A0
1  Tim
-----------------------------------
Command 7
-----------------------------------
7
Testing networks.
0  AndroidAP4AA0
>connected with IP:192.168.208.140
1  Tim
>SSID not found
   2 Networks tested, 1 OK
```

Screen 2 (right): this edited screen dump shows the output of some of the more complex commands. Note that these commands have been issued in the order shown, to add and then remove an SSID. Commands 3 and 4 require a second parameter which is a number printed by commands 2 and 1 (respectively) issued prior.



```
Time is 04:01:30 on 13/02/2023. NO NTP.
Connect failed
Connecting to 0 AndroidAP4AA0
Skip IPAPI fetch, no WiFi.

****
   NTP adjustment: 11953
****
Connected with IP: 192.168.130.138
Time is 04:01:45 on 13/02/2023. NTP OK. Last updated 0 minutes ago.
IPAPI start.
Headers of 170 bytes report 18 bytes of content.
Received 18 bytes.
HTTP finished:200
OK
Lat/Lon=-27.467899,153.032501
Time is 04:02:00 on 13/02/2023. NTP OK. Last updated 0 minutes ago.
Time is 04:02:15 on 13/02/2023. NTP OK. Last updated 0 minutes ago.
Time is 04:02:30 on 13/02/2023. NTP OK. Last updated 0 minutes ago.
Time is 04:02:45 on 13/02/2023. NTP OK. Last updated 1 minutes ago.
Time is 04:03:00 on 13/02/2023. NTP OK. Last updated 1 minutes ago.
Time is 04:03:15 on 13/02/2023. NTP OK. Last updated 1 minutes ago.
Time is 04:03:30 on 13/02/2023. NTP OK. Last updated 1 minutes ago.
Time is 04:03:45 on 13/02/2023. NTP OK. Last updated 2 minutes ago.
Time is 04:04:01 on 13/02/2023. NTP OK. Last updated 2 minutes ago.
```

Screen 3: the last few lines on this screen (using the TeraTerm serial terminal program) show that the Wi-Fi Time Source has connected to Wi-Fi and updated its time from NTP servers. The previous lines are typical of what might be seen on a normal startup.

Time Source to work with most of our clocks. A detailed list of commands, along with their use and purpose, is shown in Table 1.

Screen 2 shows the typical responses to the more common and complex commands. Most other commands require a simple response and will report a message if there is a problem.

Screen 3 shows the typical progression at startup, although events may not occur in this order. You might also see a much larger NTP adjustment; that is normal.

You can toggle the printing of GPS sentences over the USB serial port by using the I command. Screen 4 shows this; naturally, your data might be different. If you have a PC program that can process GPS data, you can use it to verify the data.

Connecting it to a clock

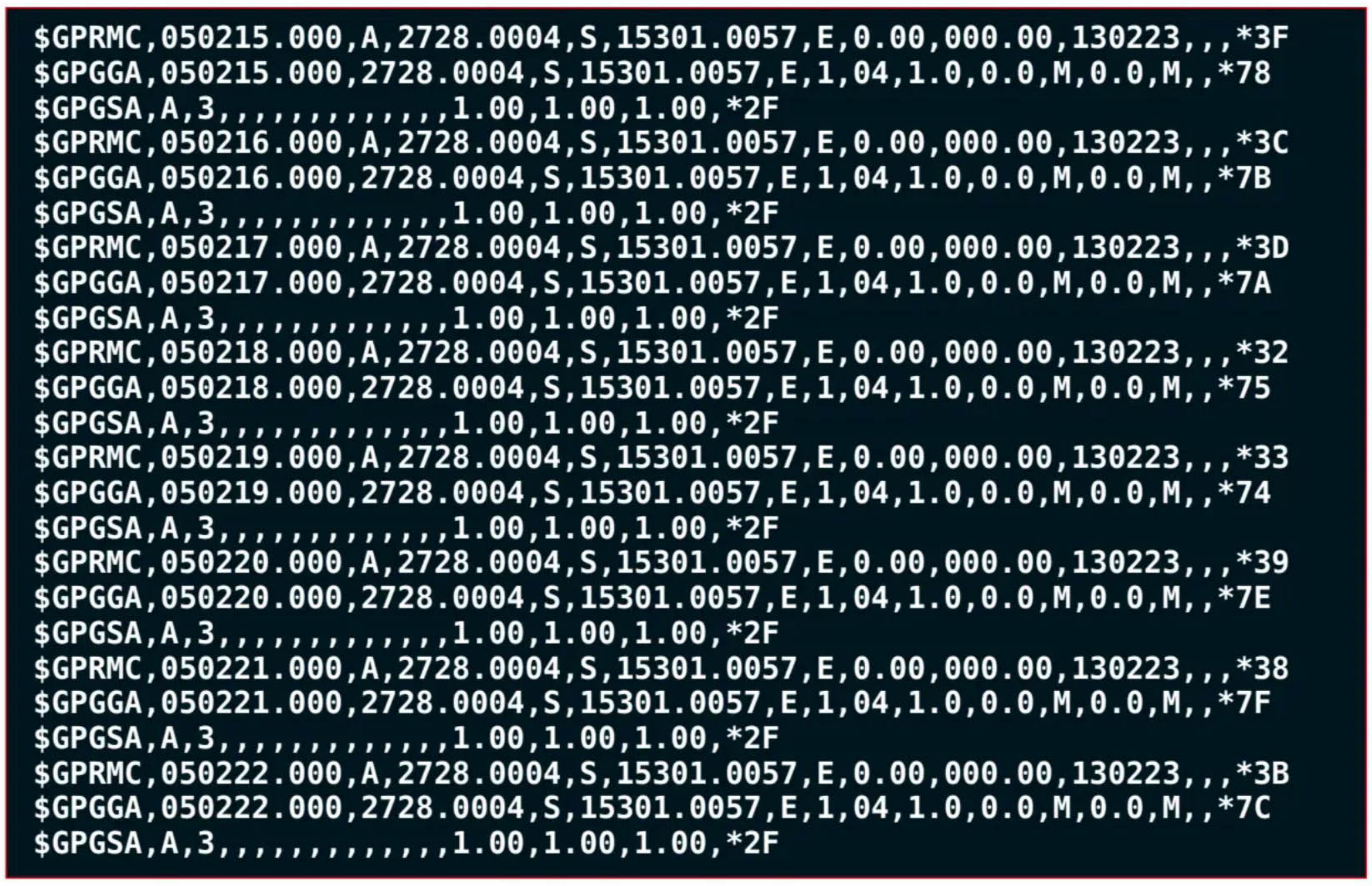
The *Wi-Fi Time Source* could feasibly connect to just about any system that expects logic level NMEA 0183 data; however, its lack of accurate speed and location data means it is not the best choice in some cases.

We don't recommend using it as the source for our GPS-based frequency references; the 1PPS signal provided by this time source is not intended to have the necessary precision.

It's not going to be much use as a navigational aid either, ruling out the *Advanced GPS Computer* from une/July 2022, so we'll assume you are using the *Wi-Fi Time Source* with one of our GPS clocks.

We have instructions below on using the *Time Source* with some GPS clock projects we have published over the last ten years. Table 2 also summarises how this *Time Source* can replace some common GPS modules.

Note that these connections may not be optimal, especially for clocks that run on batteries. You might want to experiment with alternative configurations. The suggested wiring for the recent battery-powered clocks is different to Table 2 for that reason.



```
$GPRMC,050215.000,A,2728.0004,S,15301.0057,E,0.00,000.00,130223,,,*3F
$GPGGA,050215.000,2728.0004,S,15301.0057,E,1,04,1.0,0.0,M,0.0,M,,*78
$GPGSA,A,3,,,,,,,,,,,,,1.00,1.00,1.00,*2F
$GPRMC,050216.000,A,2728.0004,S,15301.0057,E,0.00,000.00,130223,,,*3C
$GPGGA,050216.000,2728.0004,S,15301.0057,E,1,04,1.0,0.0,M,0.0,M,,*7B
$GPGSA,A,3,,,,,,,,,,,,,1.00,1.00,1.00,*2F
$GPRMC,050217.000,A,2728.0004,S,15301.0057,E,0.00,000.00,130223,,,*3D
$GPGGA,050217.000,2728.0004,S,15301.0057,E,1,04,1.0,0.0,M,0.0,M,,*7A
$GPGSA,A,3,,,,,,,,,,,,,1.00,1.00,1.00,*2F
$GPRMC,050218.000,A,2728.0004,S,15301.0057,E,0.00,000.00,130223,,,*32
$GPGGA,050218.000,2728.0004,S,15301.0057,E,1,04,1.0,0.0,M,0.0,M,,*75
$GPGSA,A,3,,,,,,,,,,,,,1.00,1.00,1.00,*2F
$GPRMC,050219.000,A,2728.0004,S,15301.0057,E,0.00,000.00,130223,,,*33
$GPGGA,050219.000,2728.0004,S,15301.0057,E,1,04,1.0,0.0,M,0.0,M,,*74
$GPGSA,A,3,,,,,,,,,,,,,1.00,1.00,1.00,*2F
$GPRMC,050220.000,A,2728.0004,S,15301.0057,E,0.00,000.00,130223,,,*39
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$GPGSA,A,3,,,,,,,,,,,,,1.00,1.00,1.00,*2F
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$GPGGA,050221.000,2728.0004,S,15301.0057,E,1,04,1.0,0.0,M,0.0,M,,*7F
$GPGSA,A,3,,,,,,,,,,,,,1.00,1.00,1.00,*2F
$GPRMC,050222.000,A,2728.0004,S,15301.0057,E,0.00,000.00,130223,,,*3B
$GPGGA,050222.000,2728.0004,S,15301.0057,E,1,04,1.0,0.0,M,0.0,M,,*7C
$GPGSA,A,3,,,,,,,,,,,,,1.00,1.00,1.00,*2F
```

Screen 4: the I command sends GPS sentences to the virtual serial terminal so that you can confirm the data being produced. This setting can be saved to flash, so the GPS data continues to be sent to the USB virtual serial port even after it reboots.

The problem is that the *Wi-Fi Time Source* has a higher current demand than most GPS modules, and the circuitry sometimes cannot provide enough current to drive it.

New GPS-Synchronised Analogue Clock – September 2023

The most recent GPS-synchronised clock was published in September 2023.

Like many of our recent GPS projects, it uses the VK2828U7G5LF GPS module. In fact, we recommend this module as a replacement for all the previous GPS modules we have used in clock projects.

The VK2828U7G5LF has six connections, but you only need four for the *Time Source*. The connections are all fairly straightforward, although they don't all connect to the GPS module header – see Fig.3.

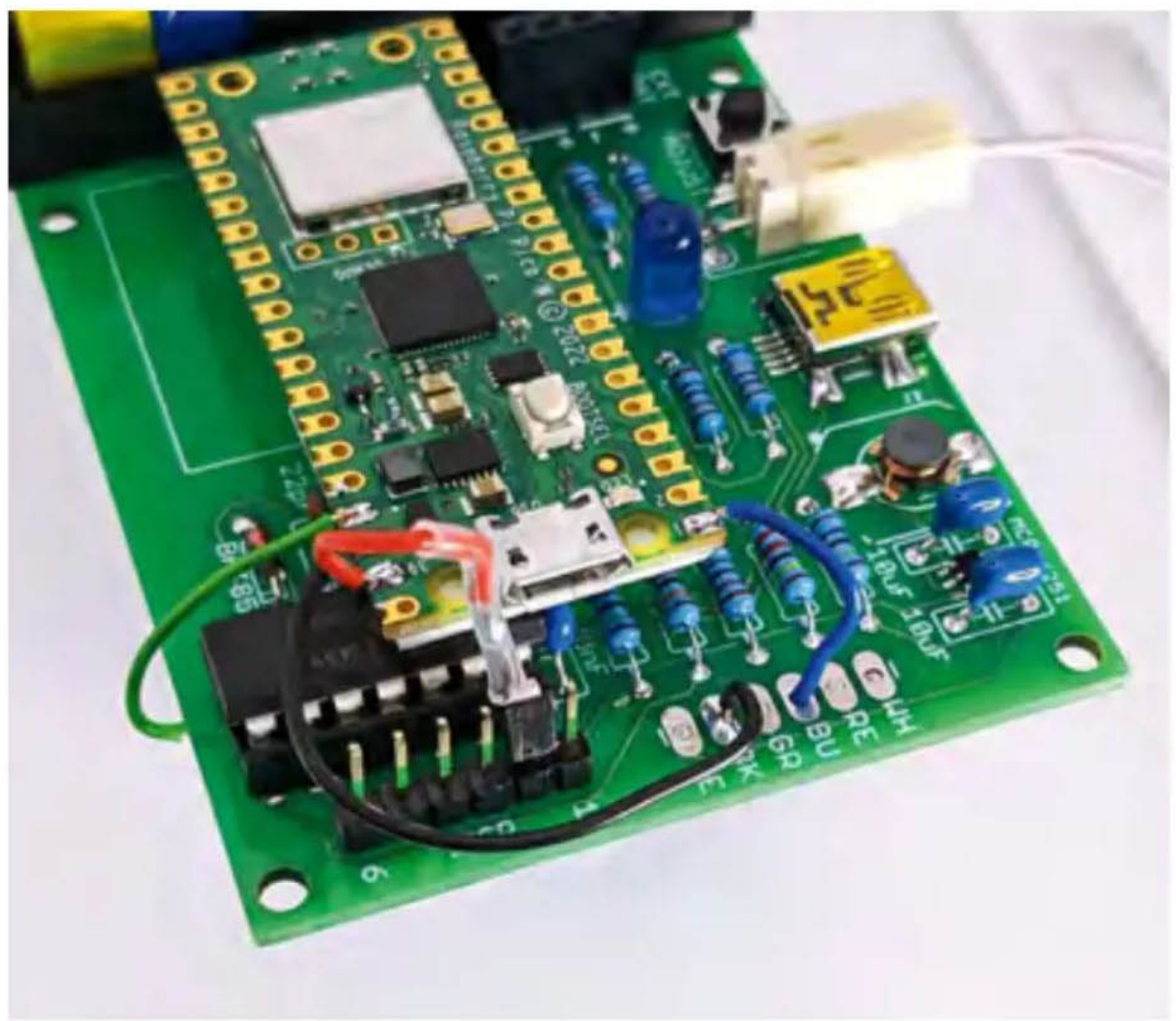
The black and blue wires are connected to the obvious points on the GPS module header. The red wire feeds power directly from the battery to the Pico W's VSYS pin; one of the pins of the ICSP header is ideal for this purpose.

Note that we've used a header pin for this connection, so power can be disconnected when we connect to the USB socket for programming. This prevents 5V from the USB cable being fed into the battery.

With just these three wires, the Pico W would run continuously. So the green wire connects the 3V3_EN pin to pin 7 of IC1 on the Clock PCB. This pin is usually used to control the Clock's boost regulator. This connects underneath the PCB, as shown in the photo, since it is easier to connect to the corresponding pad.

This scheme bypasses the boost regulator on the *New GPS-Synchronised Analogue Clock*, which is possible as the Pico W has its own buck/boost regulator. That also means that if you are building the Clock board from scratch, you can leave off the boost regulator IC and its associated components.

With this arrangement, the Pico W will power up even when the battery is down to 2V, the lower limit of the Clock. By that stage, there wasn't enough voltage to power the blue LED on the Clock, but everything else worked as expected.



The photos show the *Time Source* connected via short wires and then mounted on the ICs using a pad of double-sided tape. Note how the Pico W's Wi-Fi antenna is clear of the PCB below.

The *Wi-Fi Time Source* typically takes about 25 seconds to 'get a fix',

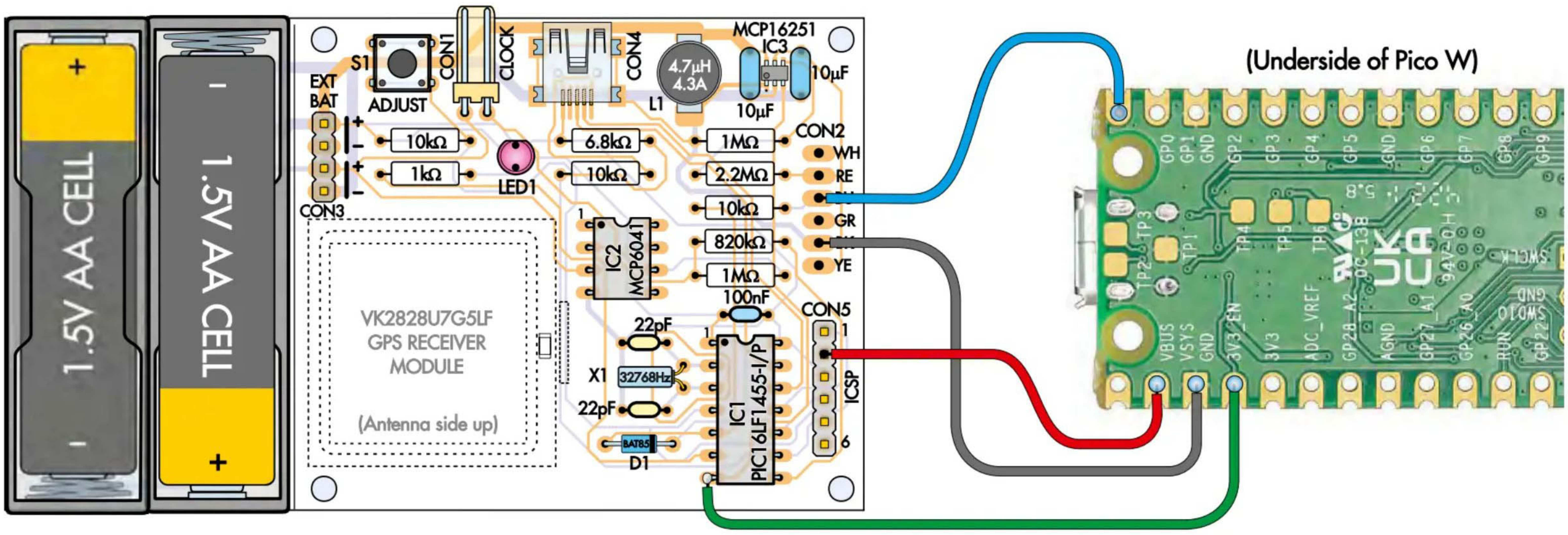

1.5V AA CELL
1.5V AA CELL
EXT BAT
S1
ADJUST
CON1
CLOCK
CON4
4.7µH 4.3A
L1
MCP16251
IC3
10µF
10µF
CON3
10kΩ
1kΩ
LED1
6.8kΩ
10kΩ
1MΩ
2.2MΩ
10kΩ
820kΩ
1MΩ
100nF
CON2
WH
RE
GR
YE
IC2 MCP6041
VK2828U7G5LF GPS RECEIVER MODULE
(Antenna side up)
22pF
X1
32768Hz
22pF
D1
BAT85
IC1 PIC16LF1455-I/P
CON5
ICSP
1
6
(Underside of Pico W)
GP0
GP1
GND
GP2
GP3
GP4
GP5
GND
GP6
GP7
GP8
GP9
VBUS
VSYS
GND
3V3_EN
3V3
ADC_VREF
GP28_A2
AGND
GP27_A1
GP26_A0
RUN
GP22

Fig.3: connecting to the New GPS-Synchronised Analogue Clock using the 3V3_EN pin on the Pico W makes the most efficient use of the Pico W's onboard boost regulator, bypassing the Clock's own boost regulator (the Pico W is shown larger than life size in Figs.3-6 for clarity). In this case, you could omit IC3, L1 and the two 10µF capacitors.

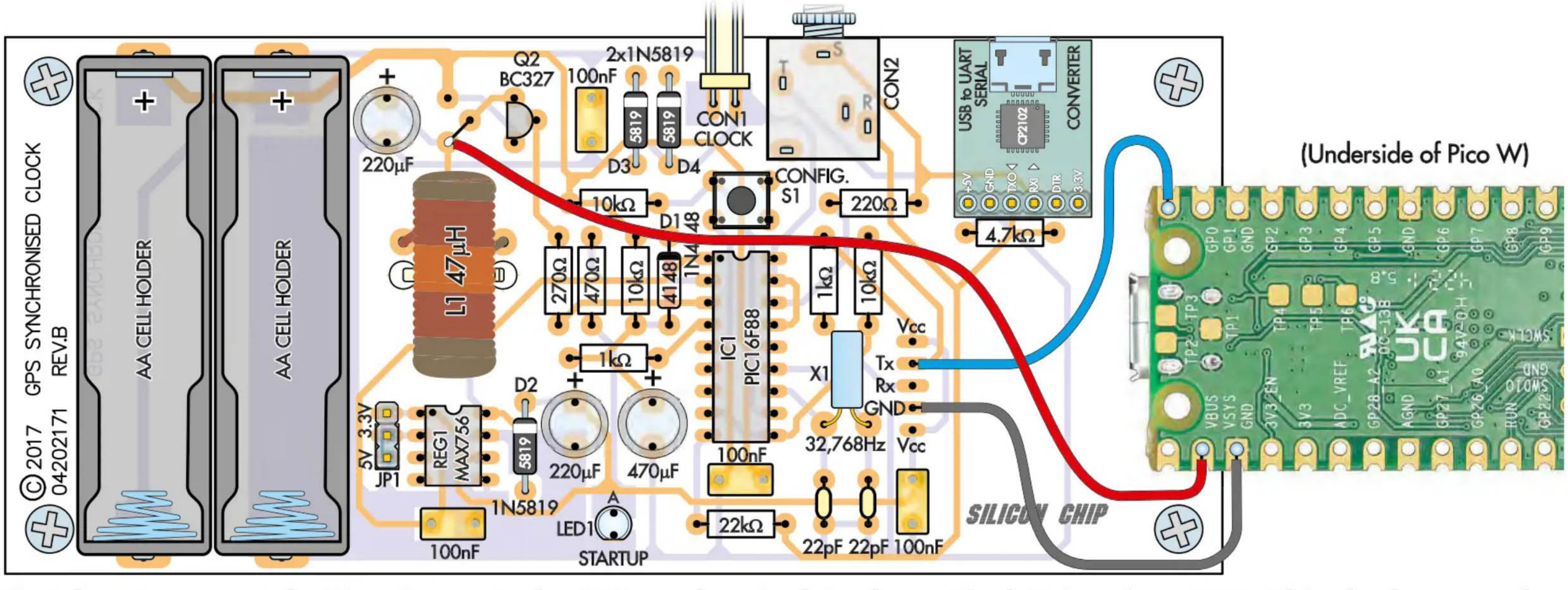
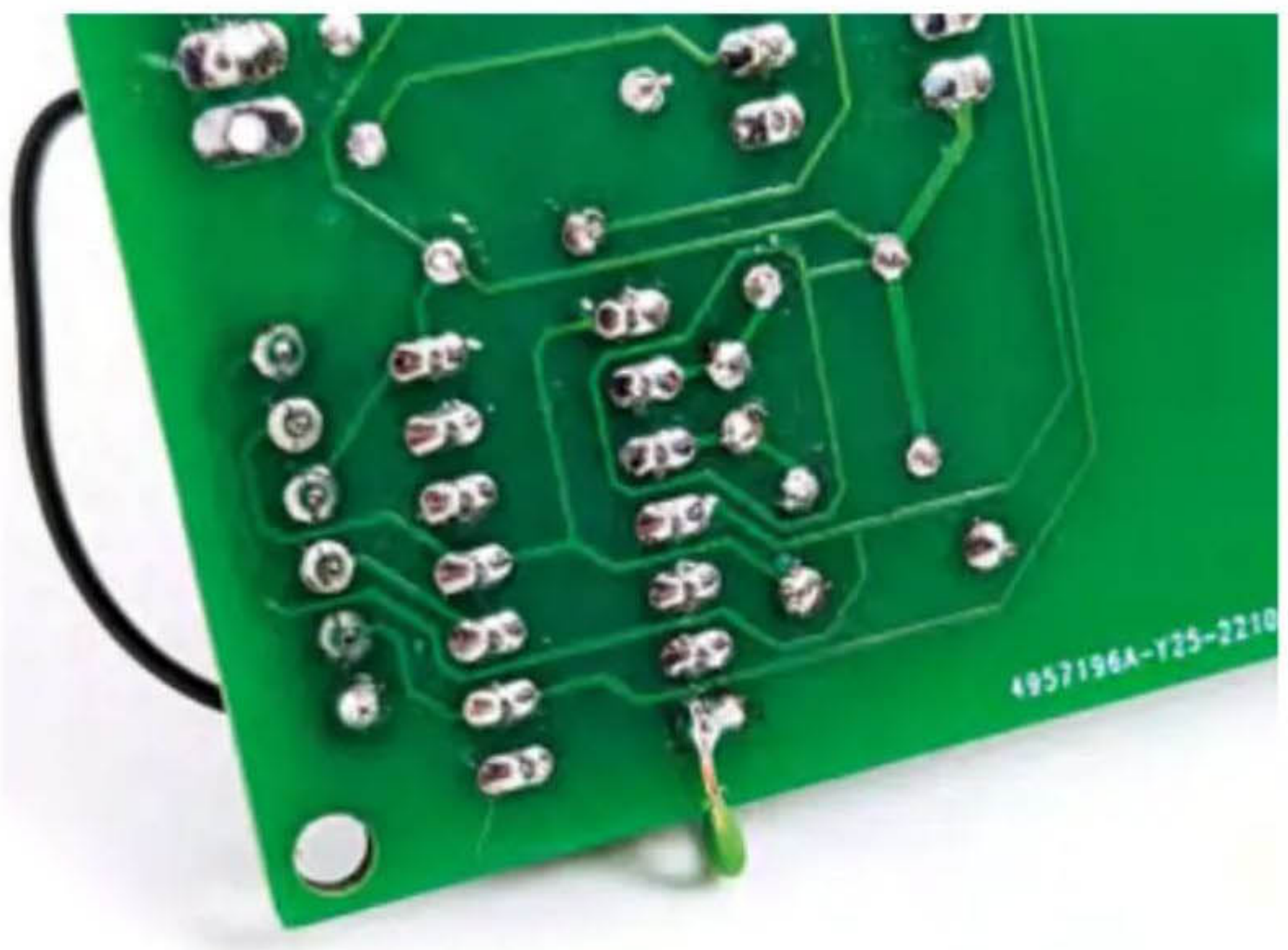
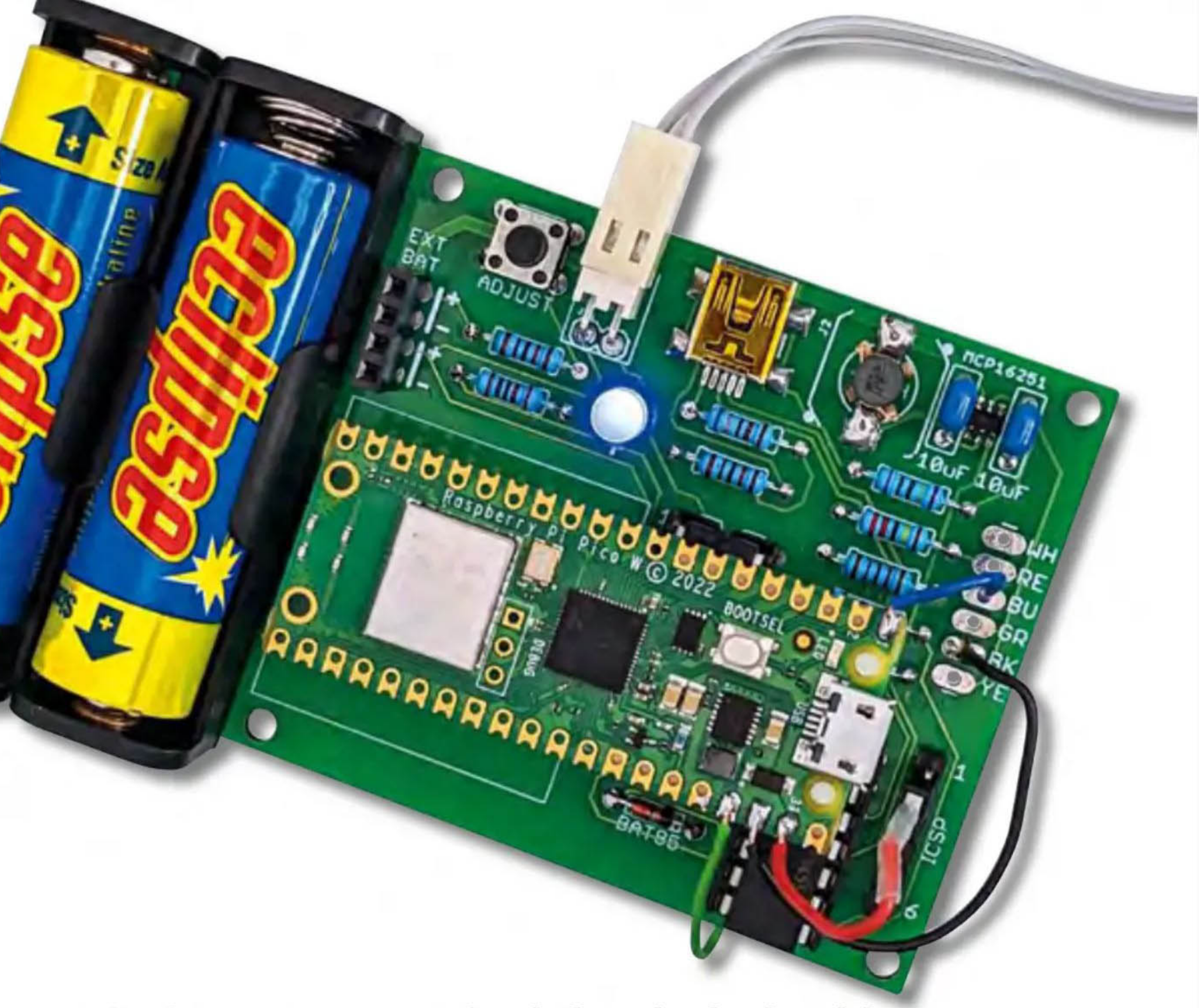

© 2017 04202171
GPS SYNCHRONISED CLOCK REV.B
AA CELL HOLDER
AA CELL HOLDER
220µF
L1 47µH
Q2 BC327
100nF
2x1N5819
D3
D4
CON1 CLOCK
CON2
CONFIG. S1
USB to UART SERIAL CONVERTER
CP2102
+5V
GND
TXO
RXI
DTR
3.3V
10kΩ
D1
1N4148
270Ω
470Ω
10kΩ
1kΩ
IC1 PIC16F88
1kΩ
10kΩ
220Ω
4.7kΩ
X1
Vcc
Tx
Rx
GND
Vcc
32,768Hz
5V 3.3V
JP1
REG1 MAX756
D2
1N5819
220µF
470µF
100nF
100nF
LED1
STARTUP
22kΩ
22pF 22pF 100nF
SILICON CHIP
(Underside of Pico W)

Fig.4: how to connect the Time Source to the GPS-synchronised Analogue Clock Driver from 2018. This also bypasses the Clock's onboard regulator to power the Pico W. Note that we have not tested this configuration.


4957196A-Y25-2210


eclipse
eclipse
EXT BAT
ADJUST
MCP16251
10uF
10uF
Raspberry Pi Pico W © 2022
BOOTSEL
WH
RE
BU
GR
BK
YE
BAT85
ICSP

The Wi-Fi Time Source wired to the New GPS-Synchronised Analogue Clock from 2023. To save battery power, the boost regulator on the clock PCB is bypassed; in fact, those onboard components could be left off entirely. The photo at upper left shows the green wire connecting directly to pin 7 of IC1 on the reverse of the PCB.

often faster and occasionally longer if it does not connect to the Wi-Fi network immediately. This should be the same with most Clocks that use the *Time Source*.

After powering on the Clock with the *Time Source* connected, the Clock would flash its LED once or twice, after which the *Time Source's* LED would come on and start flashing at the same rate as the Clock LED. After a few more seconds, the LED on the *Time Source* would turn off, showing that the Clock has obtained the correct time and powered down the *Time Source*.

Generally, the Clock LED should also turn off after half an hour at most (and the clock should start ticking), so if it continues flashing for longer than that, you should investigate.

In general, we found that if the data displayed on the USB serial terminal appeared correct, the *Time Source* would work correctly when connected to the Clock.

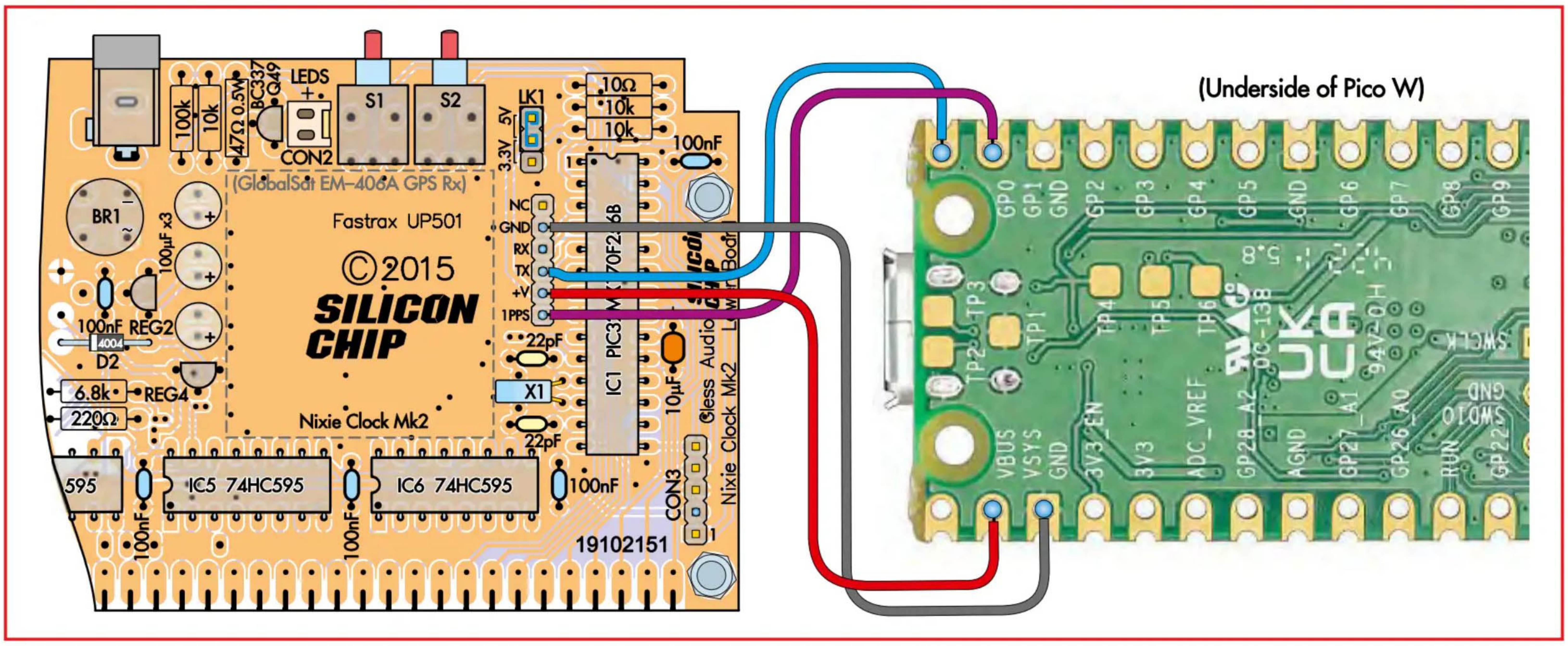

(Underside of Pico W)
GP0
GP1
GND
GP2
GP3
GP4
GP5
GND
GP6
GP7
GP8
GP9
VBUS
VSYS
GND
3V3_EN
3V3
ADC_VREF
GP28_A2
AGND
GP27_A1
GP26_A0
RUN
GP22
TP1
TP2
TP3
TP4
TP5
TP6
SWCLK
GND
SWDIO
LEDS
S1
S2
LK1
3.3V
5V
10Ω
10k
10k
100nF
100k
10k
47Ω 0.5W
BC337
Q49
CON2
(GlobalSat EM-406A GPS Rx)
Fastrax UP501
©2015
SILICON CHIP
Nixie Clock Mk2
NC
GND
RX
TX
+V
1PPS
BR1
100µF x3
100nF
REG2
4004
D2
6.8k
REG4
220Ω
22pF
X1
22pF
IC1 PIC32MX170F256B
10µF
595
IC5 74HC595
IC6 74HC595
100nF
100nF
100nF
CON3
19102151
Nixie Clock Mk2

Fig.5: connections to a 2017 Nixie Clock (not a *PE* project). LK1 (which chooses between a 3.3V and 5V supply for the connected module) should be set to the 5V position. Still, this design is not powered by a battery, so efficiency is less critical.

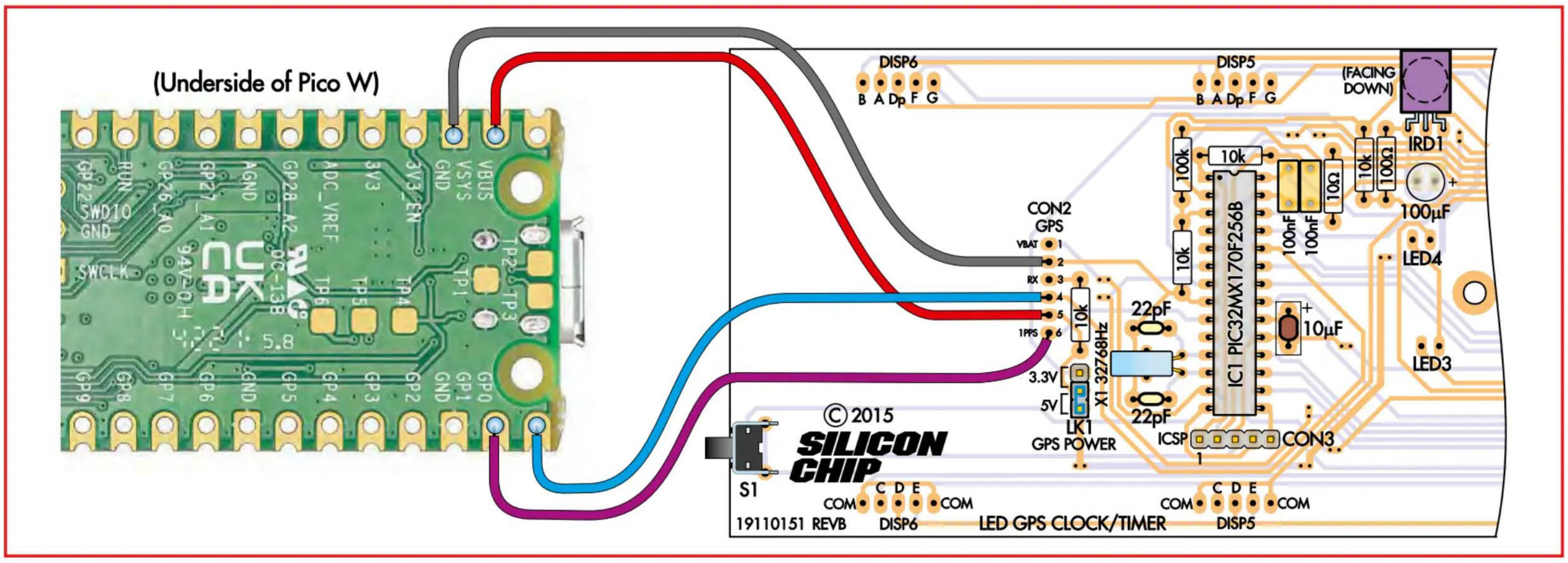

(Underside of Pico W)
GP22
RUN
GP26_A0
GP27_A1
AGND
GP28_A2
ADC_VREF
3V3
3V3_EN
GND
VSYS
VBUS
SWDIO
GND
SWCLK
TP1
TP2
TP3
TP4
TP5
TP6
GP9
GP8
GP7
GP6
GND
GP5
GP4
GP3
GP2
GND
GP1
GP0
DISP6
B A Dp F G
DISP5
B A Dp F G
(FACING DOWN)
IRD1
100µF
LED4
LED3
CON2
GPS
VBAT 1
2
RX 3
4
5
1PPS 6
10k
22pF
X1 32768Hz
22pF
3.3V
5V
LK1
GPS POWER
100k
10k
10k
IC1 PIC32MX170F256B
100nF
100nF
10Ω
10k
100Ω
10µF
ICSP
CON3
©2015
SILICON CHIP
S1
COM
C D E
COM
19110151 REVB
DISP6
LED GPS CLOCK/TIMER
COM
C D E
COM
DISP5

Fig.6: the High Visibility 6-Digit LED GPS Clock uses the same header pinout as the Nixie Clock, so the wiring is much the same, as is the choice to set LK1 to the 5V position.

Table 2 – Time Source pin mapping compared to GPS modules

Pico W	VK2828	EM408	Notes
Pin 1 GP0 (NMEA data)	TxD(4, blue)	Tx(4)	
Pin 2 GP1 (1PPS)	1PPS (6, white)	Not connected	Not needed for most applications
Pin 3/38 GND	GND (2, black)	GND(2)	
Pin 39 VSYS	VCC (5, red)	V+(5)	Or another source of 1.8V to 5.5V
Pin 40 VBUS	Not connected	Not connected	
Not needed	EN (1, yellow)	EN (1)	
Not needed	RxD (3, green)	RX(3)	

GPS-synchronised Analogue Clock Driver – February 2018

The *GPS-synchronised Analogue Clock Driver* from February 2018 also recommended the VK2828U7G5LF GPS module. Note that we have not tested this arrangement or any of the following arrangements with clocks before 2022.

Here we propose a variation that will avoid a small amount of inefficiency by also bypassing the Clock Driver's boost regulator. Since the Pico W can work from voltages down to 1.8V at VSYS, we take 3V directly from the input of the boost regulator, as shown in Fig.4.

GPS clocks from 2017

All the earlier GPS clocks we published used external power supplies, so they should not have any problems due to the limitations of a battery supply.

Fig.5 and Fig.6 show how to connect the *Wi-Fi Time Source* to the *6-Digit Retro Nixie Clock Mk.2* and *High Visibility 6-Digit LED GPS Clock*, respectively.

Note that both use the same header pinout for connections to their respective GPS modules, corresponding to the connections shown in Table 2.

For efficiency reasons, the GPS power supply voltage link for these projects (LK1 for both projects) should be set to the 5V position, since the Pico W will happily work with 5V at its VSYS input.

If you have problems after connecting the *Time Source* to one of the other clocks, it is most likely a power problem. Check that the 3V3_OUT pin is near 3.3V. If not, the circuit may not be able to supply enough current for the Pico W.

Conclusion

The Pico W board provides helpful features in roles like this, such as its integrated buck-boost power supply, dedicated USB peripheral allowing a separate configuration console and good software support.

The *Wi-Fi Time Source* is a natural progression of the original *Clayton's GPS Time Source* from 2019 and is similarly simple and well-priced. The Pico W variant adds extra features, particularly the ability to connect automatically to one of several Wi-Fi networks.

At the time of writing, Bluetooth support is in its early (beta) stages, so we will investigate if it is possible to add a Bluetooth interface for configuration. This would be very handy for updating settings as it would remove the need to connect a USB cable.

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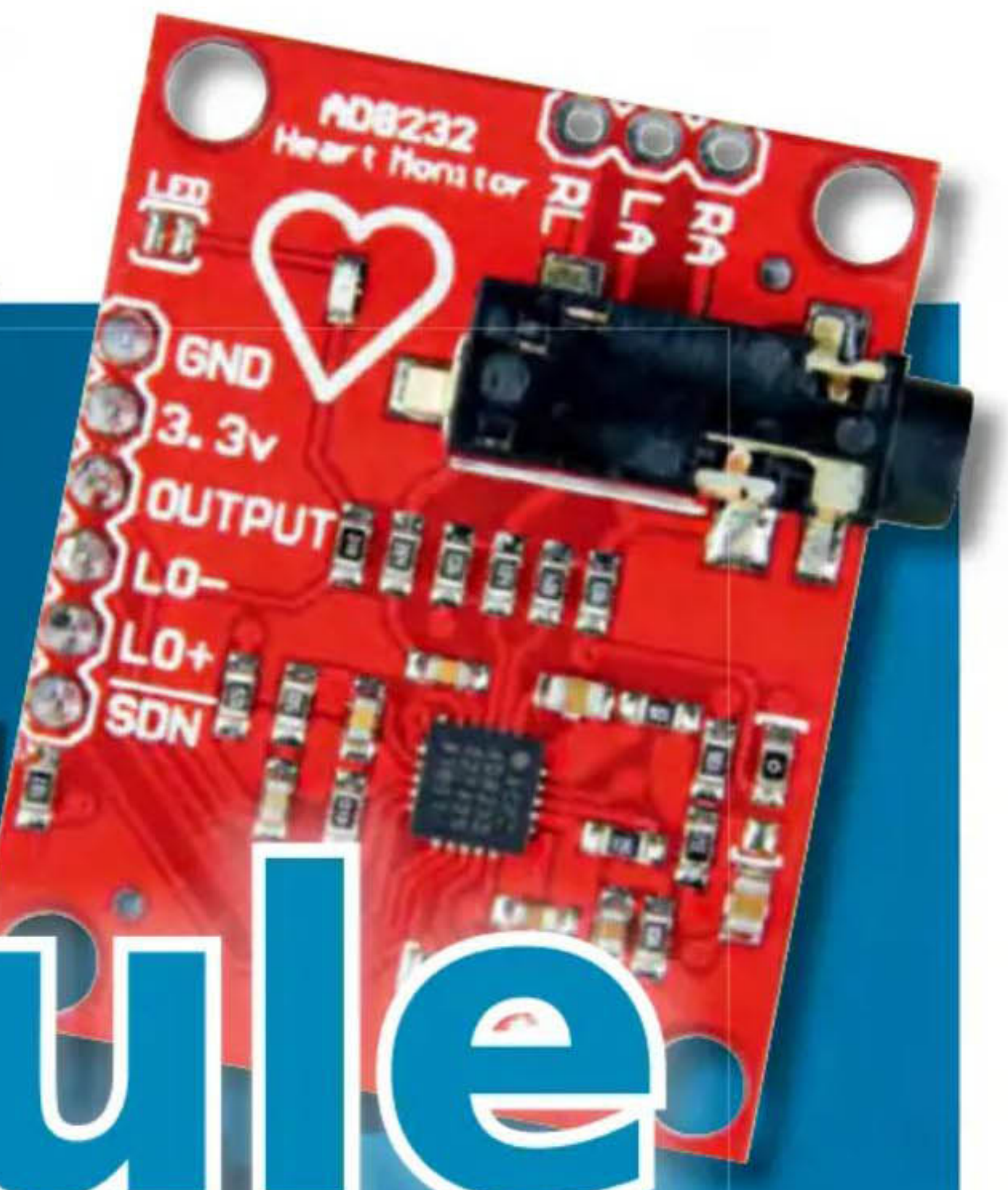
Using Electronic Modules with Jim Rowe

Heart Rate Sensor Module



This kit features an Analog Devices AD8232 heart rate monitor front-end IC which forms the 'heart' of this module. It provides a low-cost way to monitor the operation of the heart via an Arduino MCU or similar. It comes complete with a matching three-electrode lead; a pack of additional electrode pads is also available.

Electrocardiograms (ECG) are medical tools for measuring and recording the tiny voltages produced on the skin due to heart muscle activity. By attaching two, three or more electrodes or 'leads' to the skin of your wrists, ankle or chest, a professional ECG costing upwards of several thousand pounds can record ECG waveforms to allow a GP or cardiac specialist to check your heart's health.

In the October 2016 issue of *Practical Electronics*, we described an *Arduino-based USB Electrocardiogram* project which allowed you to do all of this using a Windows-based laptop PC. The project was *not* intended for use in medical diagnosis, but simply for use in exploring the way your body works. It can be fun, as well as educational.

You can monitor changes to your heart under various conditions, as it is affected by many things, including emotions, mental and physical activity – even breathing. All of these things can have a demonstrable effect on the heart's ECG waveform. Being able to show this easily, safely and at a low cost is a bonus.

To adapt an Arduino Uno module for sampling the low-level signals picked up by ECG electrodes, in 2016, I designed a small 'front-end shield' that plugged into the Arduino. It provided a high-gain (1000/2000 times) differential amplifier plus a three-pole low pass filter to reduce the sampler's susceptibility to 50Hz hum.

The heart rate sensor module we're discussing in this article is basically a much-improved version of the front-end shield in our project, compressed into a single 4mm-square 20-lead SMD chip: the Analog Devices AD8232. This is a very impressive device, as you'll soon see.

The AD8232 comes on a module from multiple online sources, which combines the AD8232-based module with a colour-coded three-electrode cable and a set of matching adhesive sensor electrode pads. Search for 'AD8232 Heart Monitor' – **amazon.co.uk** currently has this for under £10. Additional adhesive electrode pads are sold separately.

Inside the AD8232

Analog Devices describe the AD8232 as a 'Heart Rate Monitor Front End', or an 'integrated signal conditioning block for ECG and other biopotential measurement applications'.

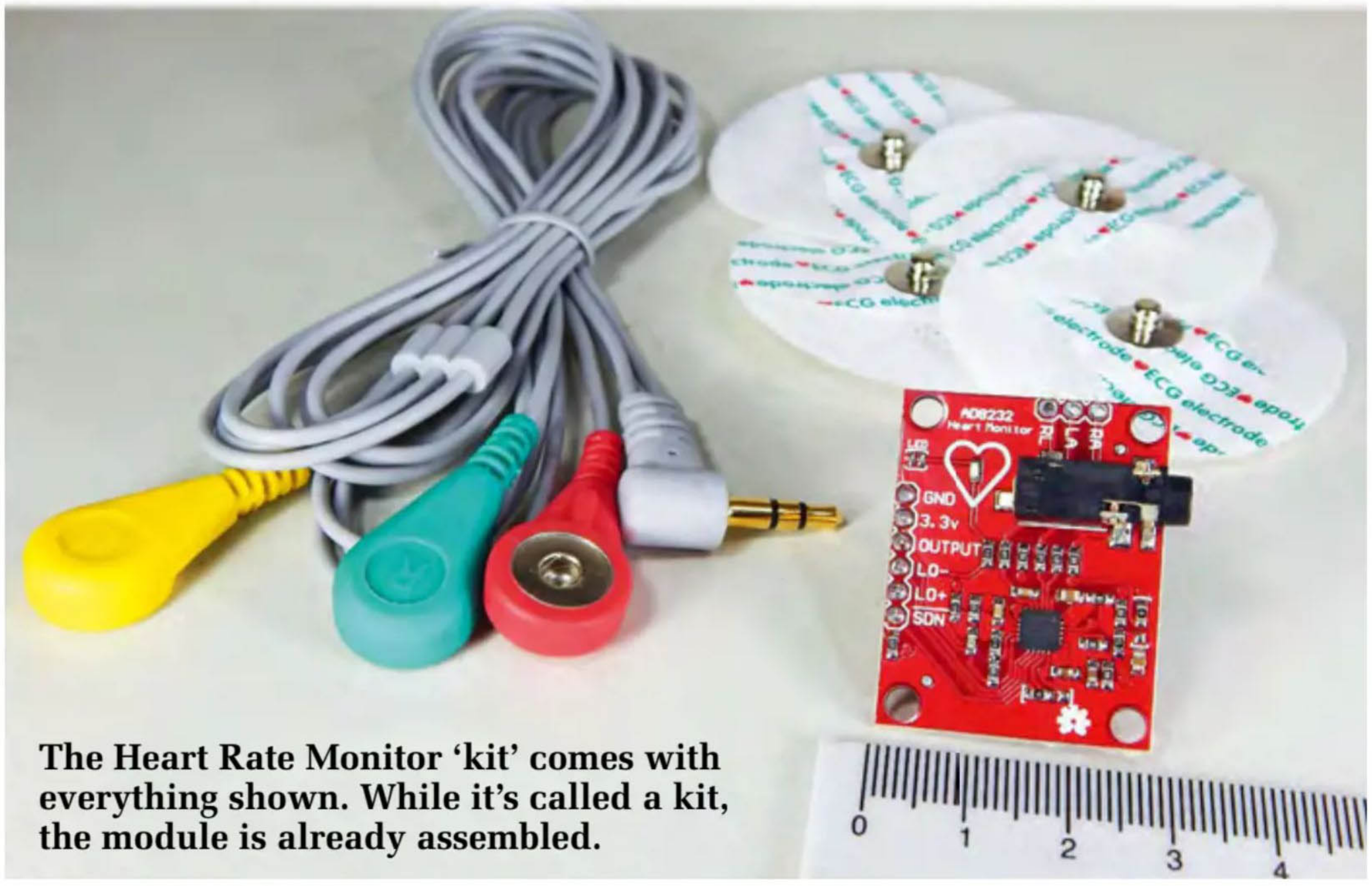
A simplified version of the circuitry inside the AD8232 is shown in Fig.1. As you can see, it includes an instrumentation amplifier (InstA) to process the incoming low-level ECG signals, plus three further op amps: A1, A2 and A3.

A1 provides low-pass and high-pass filtering plus additional gain. A3 is used to buffer the half-supply reference voltage, ensuring that the main amplifier InstA can handle the full signal swing.

A2 is used to drive the right-leg electrode lead (RLD) with an inverted version of any common-mode signal present in the inputs to the instrumentation amplifier, InstA. This improves the common-mode rejection of the system, giving a significantly cleaner reproduction of the ECG signal.

There are also two comparators, C1 and C2, used to provide 'lead-off' signals if either of the main electrodes is not in good contact with the skin of the wrists or arms.

The result of this complexity inside the AD8232 chip is that when its inputs are connected to electrodes attached to the skin of a human body, and it's provided with suitable support circuitry, it gives a clean analogue ECG output signal.



The Heart Rate Monitor 'kit' comes with everything shown. While it's called a kit, the module is already assembled.

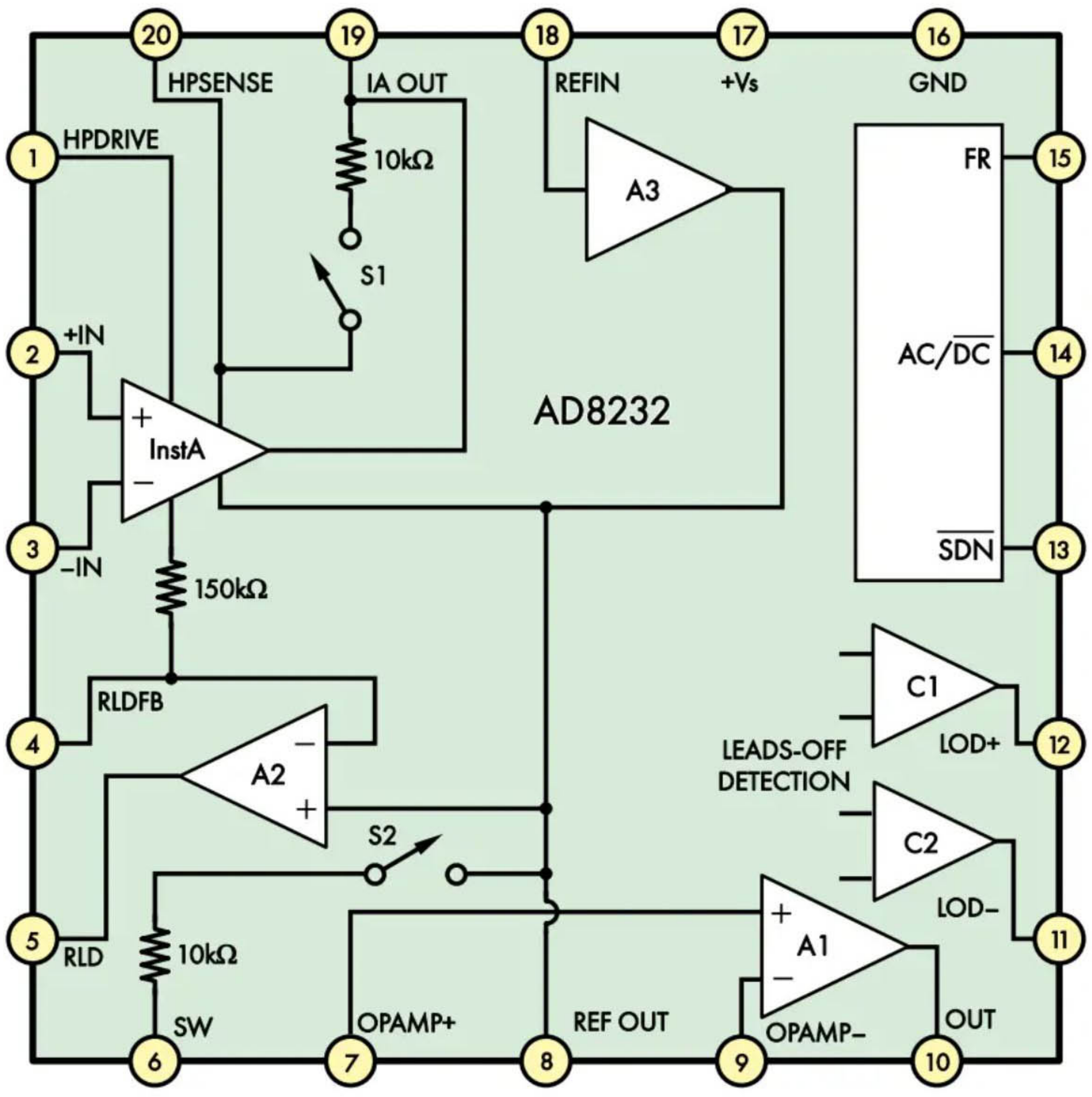

20
19
18
17
16
HPSENSE
IA OUT
REFIN
+Vs
GND
1
HPDRIVE
10kΩ
A3
FR
15
S1
2
+IN
AD8232
AC/DC
14
InstA
3
–IN
150kΩ
SDN
13
RLDFB
C1
4
A2
LEADS-OFF DETECTION
LOD+
12
S2
C2
LOD–
5
RLD
10kΩ
A1
11
SW
OPAMP+
REF OUT
OPAMP–
OUT
6
7
8
9
10

Fig.1: a simplified block diagram of the AD8232 IC. It's described as a single-lead ECG front-end and implements various low- and high-pass filters using internal op amps.

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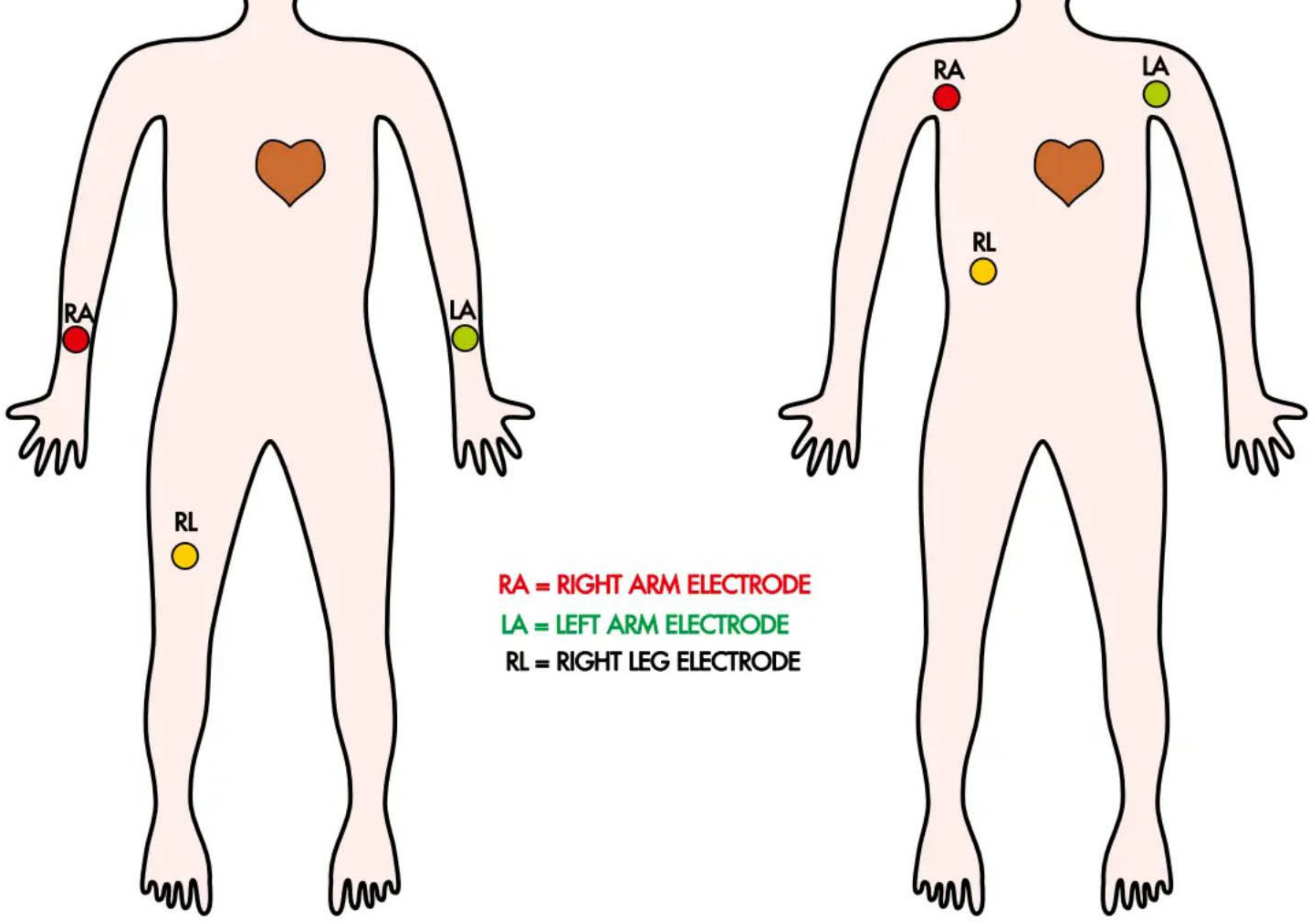

RA
LA
RL
RA
LA
RL
RA = RIGHT ARM ELECTRODE
LA = LEFT ARM ELECTRODE
RL = RIGHT LEG ELECTRODE

Fig.3: the typical electrode placements on the human body. Note the orientation of the person is such that their face is looking out of the page.

The module circuit

Fig.2 shows the full circuit of the AD8232-based module. There's very little in it apart from the AD8232 chip and a handful of passive components. It all fits on a small PCB measuring 30 × 35mm, including the mini 3.5mm TRS jack socket used to connect the three-electrode lead.

Connectors CON1 and CON2 provide alternative connections for the input electrodes: CON2 is the 3.5mm input jack and CON1 is just a set of three holes in the PCB to receive a 3-pin SIL header. CON3 is a 6-pin SIL header that provides all the power and output connections.

As the labels suggest, pins 1 and 2 of CON3 are used for ground and +3.3V power, respectively; pin 3 is the ECG signal output, while pins 4 and 5 provide the 'lead-off' error signals.

Pin 6 of CON3 is a logic input that allows the AD8232 to be placed in shutdown (standby) mode to save power when ECG readings are not needed. It is normally pulled high by a 10kΩ resistor, so all that is required to place it in standby mode is to pull it low.

The rated current drain of the AD8232 chip is less than 250µA in operating mode, dropping to less than 500nA (0.5µA) in shutdown/standby mode. So the module is suitable for battery-powered portable use.

As well as being taken to pin 3 of CON3, the ECG output from pin 10 of IC1 also connects to LED1 via a 1kΩ series resistor. This allows the LED to be used to monitor the heartbeat visually. But if this is not required, the LED can be disabled simply by cutting the PCB track between the two pads of LK1.

LED1 is on the module PCB at upper left, in the centre of the printed 'heart' symbol. LK1 is visible just to the left of the 'heart', above the connections for CON3. The latter is fitted underneath the PCB, ready to connect to a breadboard or another PCB.

Electrode placement

Fig.3 shows two of the suggested placements of the three electrodes with this kind of ECG sensor.

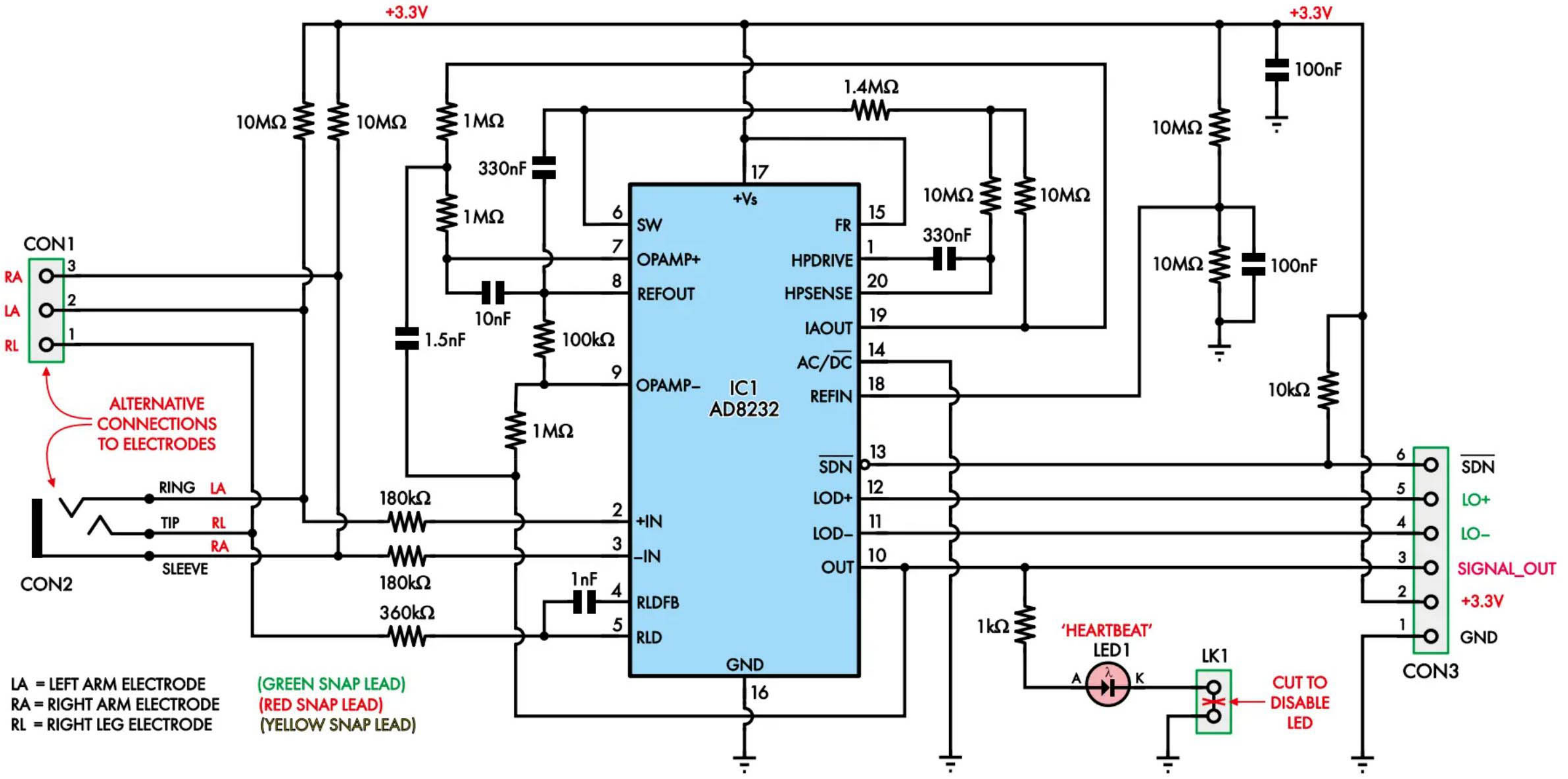

+3.3V
+3.3V
100nF
1.4MΩ
10MΩ
10MΩ
1MΩ
330nF
1MΩ
10MΩ
10MΩ
10MΩ
10MΩ
100nF
17
+Vs
6
SW
FR
15
7
OPAMP+
HPDRIVE
1
330nF
8
REFOUT
HPSENSE
20
10nF
1.5nF
100kΩ
IAOUT
19
AC/DC
14
9
OPAMP–
IC1
AD8232
REFIN
18
10kΩ
1MΩ
CON1
RA
LA
RL
3
2
1
ALTERNATIVE CONNECTIONS TO ELECTRODES
SDN
13
6
SDN
LOD+
12
5
LO+
RING LA
180kΩ
2
+IN
LOD–
11
4
LO–
TIP RL
RA
3
–IN
OUT
10
3
SIGNAL_OUT
SLEEVE
180kΩ
1nF
2
+3.3V
CON2
360kΩ
4
RLDFB
1kΩ
'HEARTBEAT' LED1
1
GND
5
RLD
GND
A
K
LK1
CON3
16
CUT TO DISABLE LED
LA = LEFT ARM ELECTRODE (GREEN SNAP LEAD)
RA = RIGHT ARM ELECTRODE (RED SNAP LEAD)
RL = RIGHT LEG ELECTRODE (YELLOW SNAP LEAD)

Fig.2: the full circuit of the heart rate monitor module. Apart from IC1 and LED1 the circuit consists of a small number of passive components. The module also features alternative input connectors (CON1 and CON2) for the electrodes.

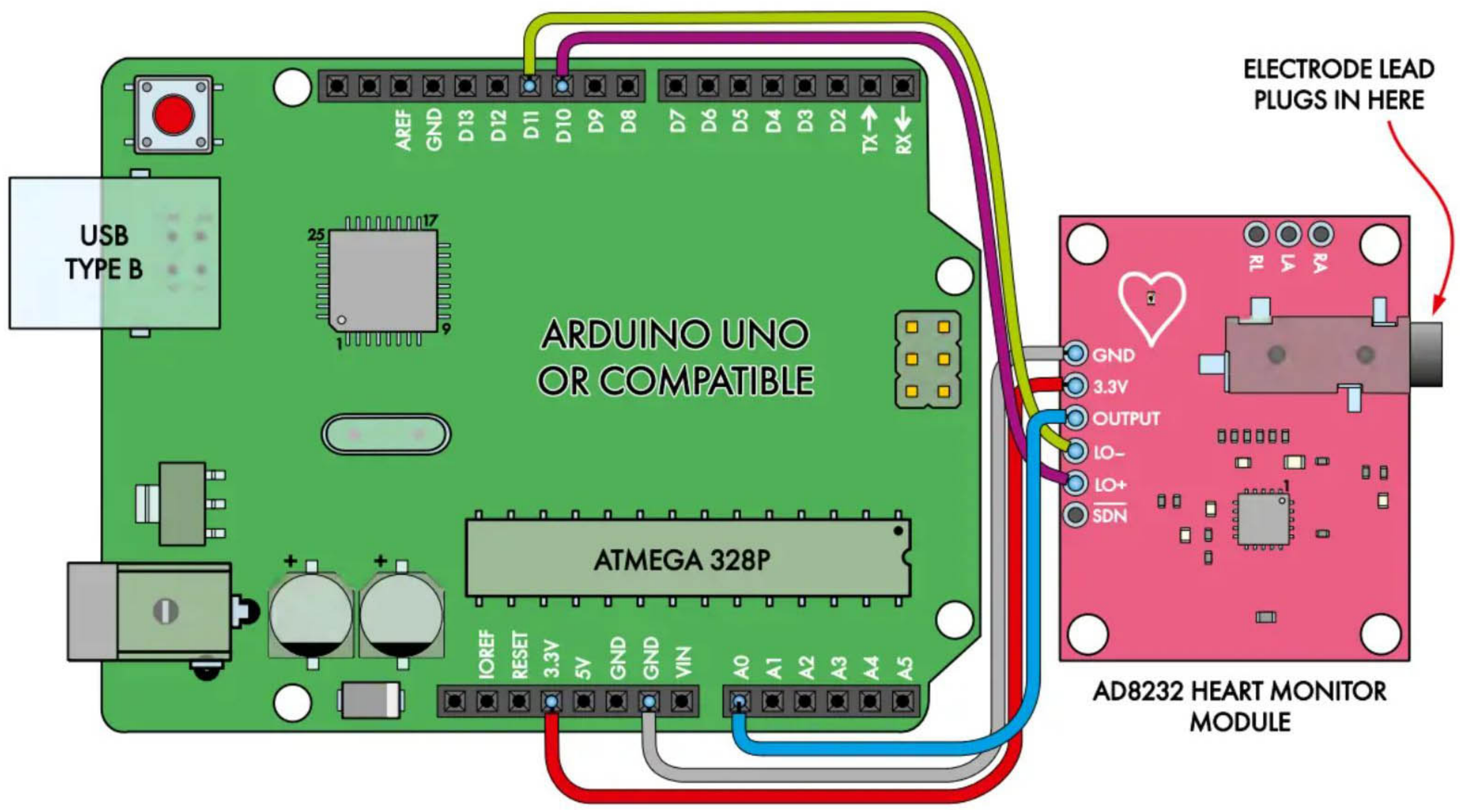

ELECTRODE LEAD PLUGS IN HERE
USB TYPE B
AREF
GND
D13
D12
D11
D10
D9
D8
D7
D6
D5
D4
D3
D2
TX→
RX←
ARDUINO UNO OR COMPATIBLE
ATMEGA 328P
IOREF
RESET
3.3V
5V
GND
GND
VIN
A0
A1
A2
A3
A4
A5
RL
LA
RA
GND
3.3V
OUTPUT
LO–
LO+
SDN
AD8232 HEART MONITOR MODULE

Fig.4 (above): the connection diagram for the heart rate monitor module to an Arduino Uno or similar.

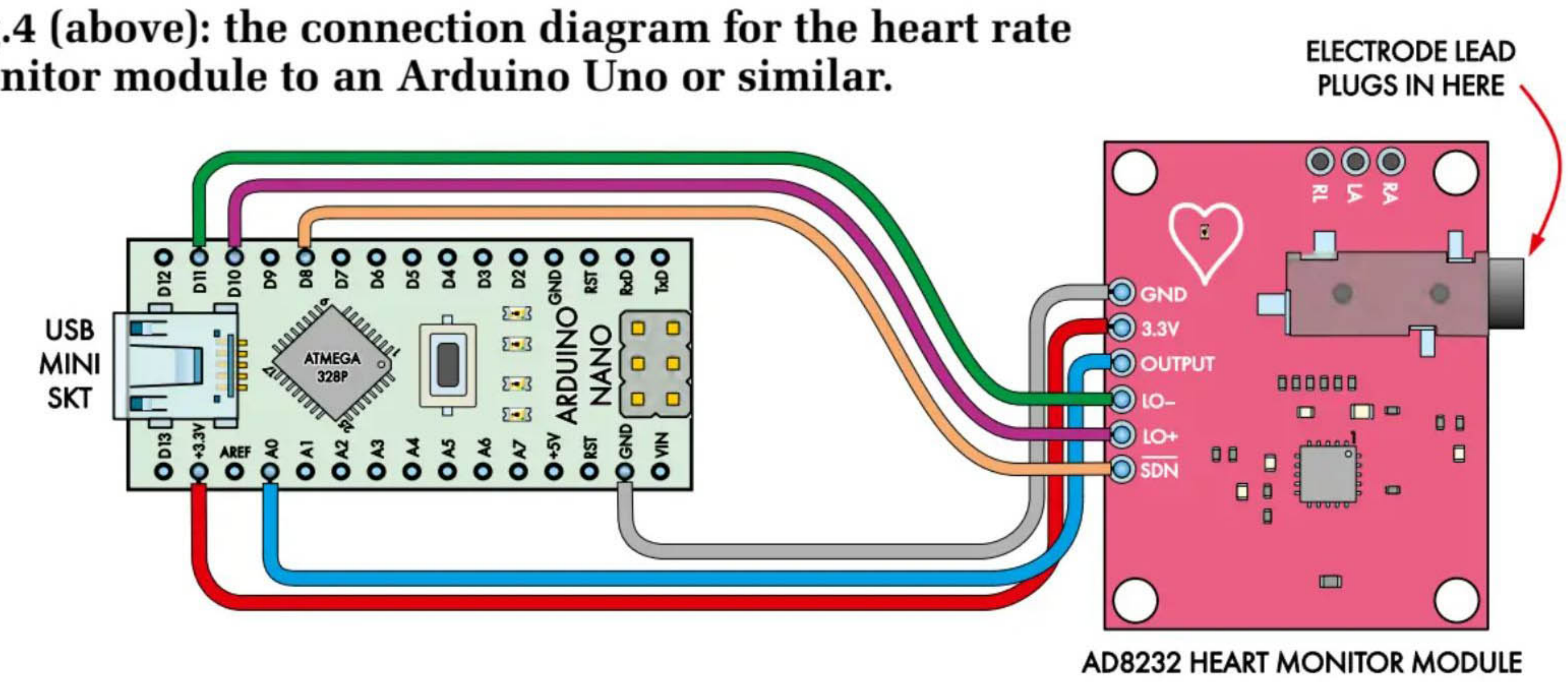

ELECTRODE LEAD PLUGS IN HERE
USB MINI SKT
D12
D11
D10
D9
D8
D7
D6
D5
D4
D3
D2
GND
RST
RxD
TxD
ATMEGA 328P
ARDUINO NANO
D13
+3.3V
AREF
A0
A1
A2
A3
A4
A5
A6
A7
+5V
RST
GND
VIN
RL
LA
RA
GND
3.3V
OUTPUT
LO–
LO+
SDN
AD8232 HEART MONITOR MODULE

Fig.5: the connection diagram to an Arduino Nano.

On the left, the RA (right arm) electrode is positioned near the right wrist, the LA (left arm) electrode near the left wrist and the RL (right leg) driving electrode is above the right knee. However, another suitable position is just above the right ankle.

On the right is another way of achieving much the same result. Here the RA and LA electrodes are placed just above the armpit on each side, while the RL electrode is placed on the abdomen just below the rib cage. Although it's shown to the right, it can be placed in the centre, just above the navel.

Connecting it to an Arduino

It's pretty easy to connect the AD8232 Heart Monitor module to an Arduino like the standard Uno or one of the many compatibles, as shown in Fig.4. The GND and +3.3V pins on CON3 connect to the corresponding pins on the Uno, as shown by the grey and red wires, while the OUTPUT pin connects to the A0 pin of the Uno (blue wire).

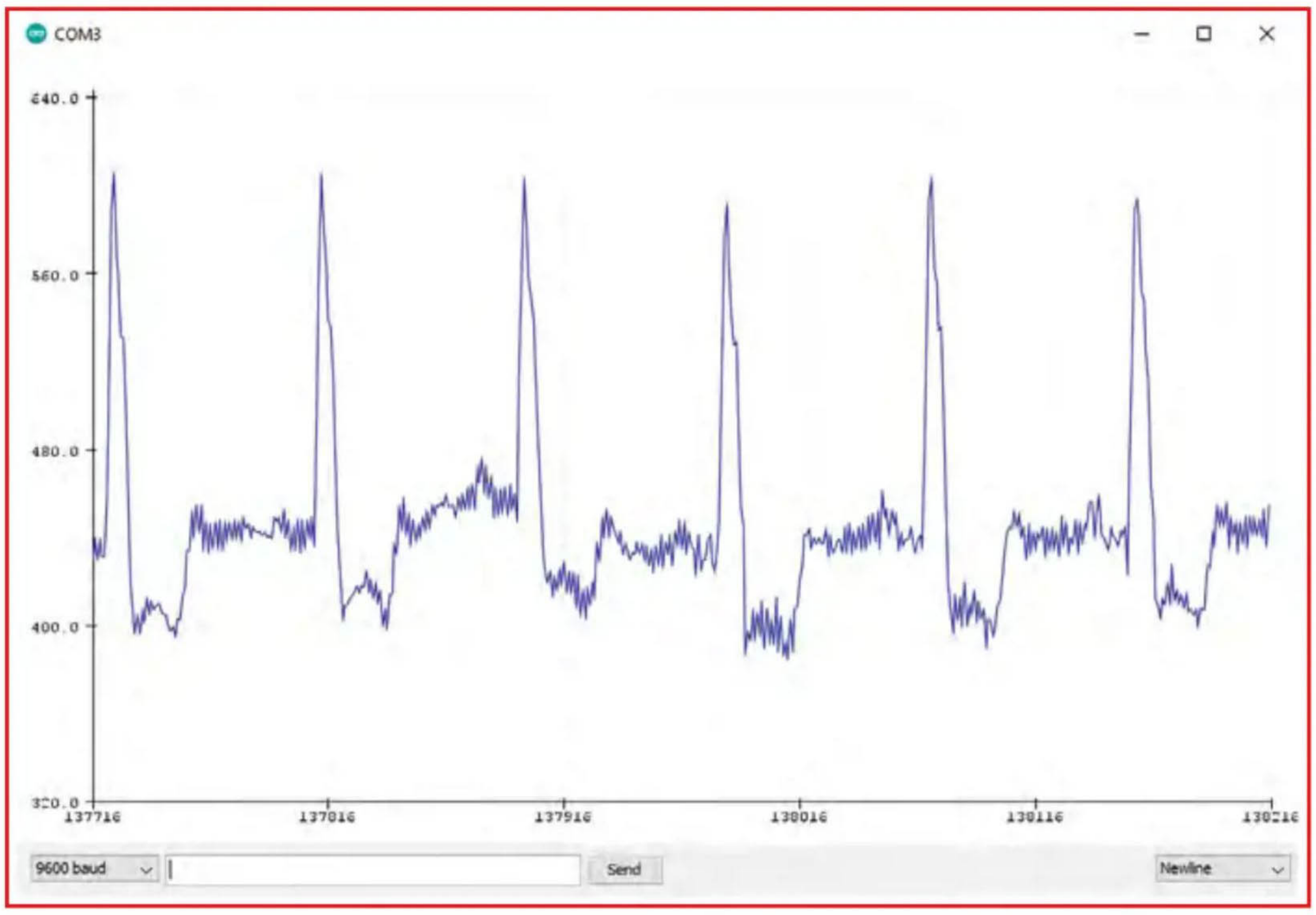

COM3
640.0
560.0
480.0
400.0
320.0
137716
137816
137916
138016
138116
138216
9600 baud
Send
Newline

Fig.6: a heart rate plot taken using the sample software and the Arduino IDE's built-in Serial Plotter.

If you want to try using the LO- and LO+ pins, these can be connected to the Uno's IO11 and IO10 pins (green and purple wires). And if you envisage wanting to make use of the $\overline{\text{SDN}}$ pin (pin 6) to save power, this can be connected to the Uno's D8 pin (not shown in Fig.4).

It's also relatively easy to connect the module to an Arduino Nano, as shown in Fig.5. Note that the connections shown in both Fig.4 and Fig.5 are those expected by the sketches I found to put the module to use. Other configurations are possible as long as the software is adapted to match.

Firmware and software

I couldn't find sketches or PC software on my vendor's (Jaycar) website for use with this module, but after searching the internet, I found references on Sparkfun's website to a simple sketch called, **Heart_Rate_Display.ino**, available to download from: **https://github.com/sparkfun/AD8232_Heart_Rate_Monitor**

This sketch was written by Casey Kuhns at SparkFun Electronics and seems to have been written originally for the Mini Arduino Pro. It simply sends numeric samples of the ECG signal back to the PC, where they can be displayed as a listing in the Arduino IDE's Serial Monitor.

If you have a recent IDE version (v1.6.6 or later), you can display them as a waveform using the Serial Plotter tool instead.

To try out the module and kit with an Arduino Uno, I adapted the Kuhns/SparkFun sketch to make it work with the Uno. The adapted sketch is called **AD8232_heart_monitor_basic.ino** and is available for download from the June 2024 page of the *PE* website: **https://bit.ly/pe-downloads**

Trying it out

I connected the Jaycar XC3784 module up to an Arduino Uno, as shown in Fig.4, then connected the Uno to a PC via a USB cable. After that, I started the Arduino IDE (v1.8.19), opened the **AD8232_heart_monitor_basic.ino** sketch, verified and compiled it.

Next, I connected the plug on the end of the electrode cable into the 3.5mm jack on the module and fitted the red electrode to my right wrist, the green electrode to my left wrist, and the yellow electrode to my right leg just behind the knee.

The next step was to upload the compiled sketch to the Arduino, after which it began running, with the little 'heartbeat' LED on the module blinking away cheerfully. When I opened the IDE's Serial Monitor tool, I was greeted by a scrolling list of numeric samples of my ECG waveform.

Of course, it is not easy to deduce much from a scrolling list of numbers, so I closed the Serial Monitor tool and opened up the Serial Plotter tool instead. This gave a waveform that was a lot easier to interpret, although there was a fair bit of noise present. So I tried moving the electrode positions a few times and kept checking the result.

The plot shown in Fig.6 is about the best I could get, and as you can see, there's still a fair bit of noise between the main QRS spikes, almost obscuring the smaller P and T bumps.

Conclusion

Although I think some of this noise could be removed by further experimenting with electrode placement, I also gained the impression that some of it was being picked up by the AD8232 module itself and the wiring between it and the Arduino.

I suspect that, for the best results, it would be a good idea to place the module and the Arduino inside an earthed metal box.

The AD8232 module and accompanying electrode kit provide an easy way to check your heart rate. If you get one, I suggest you also get one or two of the packs of extra electrode pads, since the pads are only suitable for a single use.

Your heart and its electrical activity

Most people know that your heart is basically a pump that pushes your blood around your body via its blood vessel 'plumbing' – the arteries and veins. The typical human adult heart is about the size of a clenched fist and weighs about 300g. It's located near the centre of your chest and pumps about once per second.

The pumping action is triggered mainly by a nerve centre inside the heart, called the sino-atrial (SA) node. Each pumping cycle is initiated by a nerve impulse that starts at the SA node and spreads down through the heart via preset pathways.

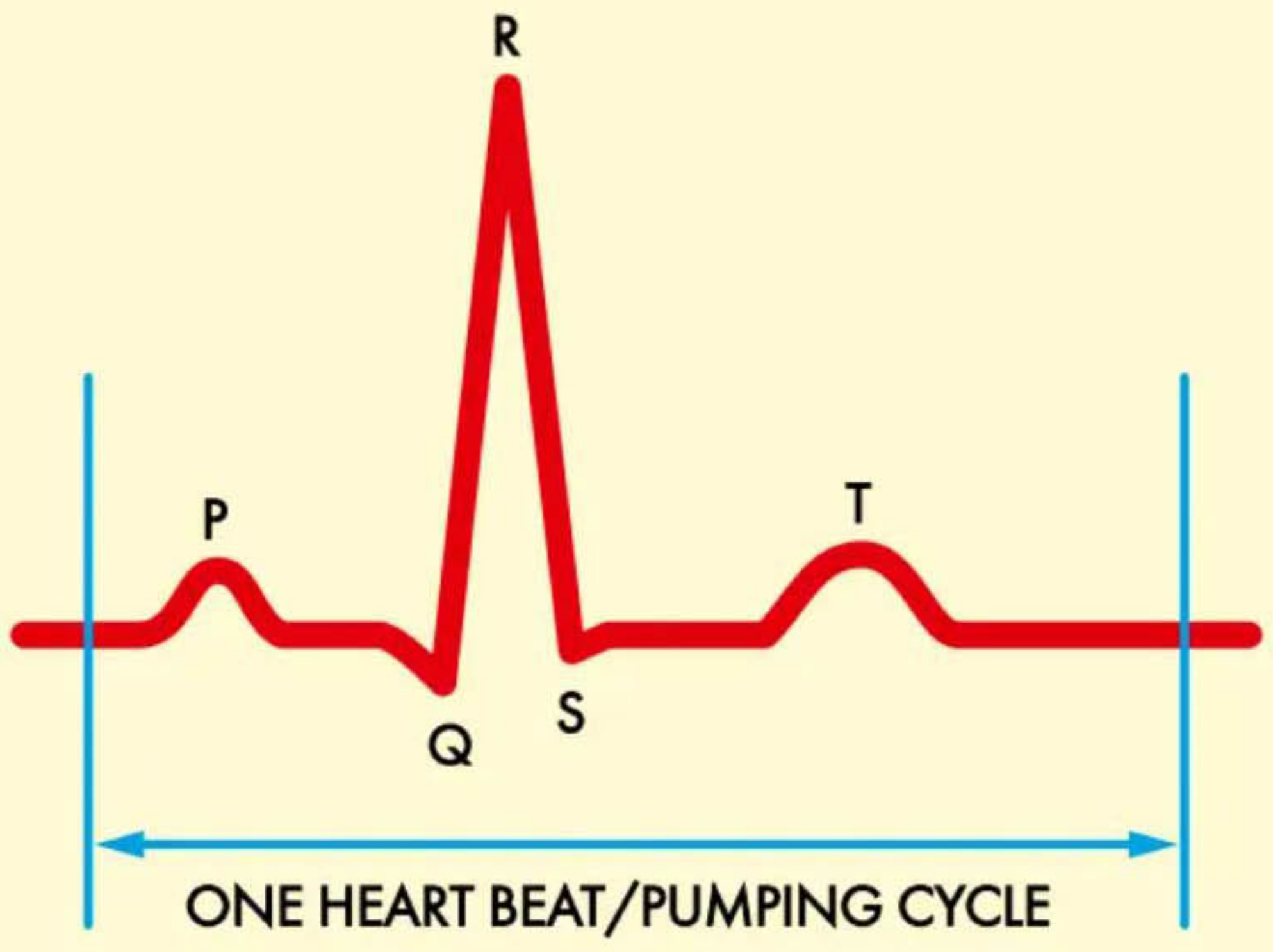
The heart comprises millions of bundles of microscopic muscle cells, which contract when triggered. The muscle cells are electrically polarised, like tiny electrolytic capacitors (positive outside, negative inside). As the trigger pulse from the SA node passes through them, they depolarise briefly and contract.

So with each beat of the heart, a 'wave' of depolarisation sweeps from the top of the heart to the bottom. Weak voltages produced by this wave appear on the outside surface of your skin, and can be picked up using electrodes strapped to your wrists, ankles and the front of your chest. It's these voltages (about 1mV peak-to-peak) that are captured and recorded as an electrocardiogram or 'ECG'.

The actual shape and amplitude of the ECG waveform depend upon the individual being examined and the positioning of the electrodes, but the general shape is shown in the adjacent graph.

The initial 'P' wave is due to the heart's atria (upper input chambers) depolarising, while the relatively larger and narrower 'QRS complex' section is due to the much stronger ventricles (lower output chambers) depolarising. Finally, the 'T' wave is due to the repolarisation of the ventricles, ready for another cycle.

Doctors can evaluate several heart problems by measuring the timing of these wave components and their relative heights. They can also diagnose problems by seeing how wave components change with the various standard electrode and lead connections.



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Solutions for: PIC . dsPIC . ARM . MSP430 . Atmel . Generic JTAG . Altera Xilinx . BDM . C2000 . SPY-BI-WIRE . SPI / IIC . Altium Mini-HDMI . & More
www.PlugOfNails.com
Tag-Connector footprints as small as 0.02 sq. inch (0.13 sq cm)

Author and Designer: Phil Prosser

LOUDSPEAKER TEST JIG

speaker
Atten 20dB
Spkr Test
Gain 20dB
MIC
Comp Test
Gain 0dB

Use your PC's sound card to measure loudspeaker performance, inductors, capacitors and complex impedances. With this Jig and appropriate software, measuring and tweaking crossovers, cabinets and speakers is easy.

When designing or building loudspeakers, you need a good microphone and test setup and the ability to measure the impedance of the loudspeaker driver and crossover parts. You can do this at home with our *Loudspeaker Test Jig*, without breaking the bank.

It is an interface to your PC, allowing you to measure complex impedances, which is important when building crossovers. This is one job where even the best multimeter doesn't help, as impedance is frequency dependent, with real and imaginary components. The *Test Jig* also connects to a microphone for analysing loudspeakers.

Fig.1 is the impedance and phase plot of a 12-inch (305mm) driver, a PA bass-mid with a resonant frequency of 60Hz. The dotted phase line goes through an inflection at this frequency, from about +55° degrees to -55°.

It is possible to make this sort of plot using an oscilloscope and graph paper, but your PC and sound card can make this sort of measurement in seconds with our *Test Jig*. Eric Wallin is credited with originating the basic concept of the 'Wallin Jig', shown in Fig.2. It is the de facto standard for PC-based speaker testing.

It uses the left output channel of the sound card output to drive a signal through a reference resistor and the device under test (DUT). The left input channel measures the voltage across both the reference and DUT, while the right input channel measures the voltage across the DUT alone.

For a complete test setup, you need:

- A PC or Mac with a sound card
- Test software. We recommend 'Room EQ Wizard' (REW, Windows/Mac) or the old but good 'Speaker Workshop' (Windows only). Both are available for free.
- A measurement microphone
- The *Loudspeaker Test Jig*, which includes:
  - An audio power amplifier of a few watts
  - A microphone preamplifier
  - A reference resistor of a few watts capacity that is 'calibrated'
  - A switching arrangement

It is also very useful to have:

- A monitor output for the audio input to the *Test Jig*, allowing both monitoring and regular use of the sound card when not testing
- An oscilloscope to monitor the microphone signal on the front panel

Two handy features this design provides are floating power for the *Test Jig* to avoid earth-loop-induced hum and switchable gain on the input and microphone to allow for 'near field' and 'far field' tests.

Software support

The software does the heavy lifting in this design. The most current program that can be used is 'Room EQ Wizard' (REW), currently in development and available at: **www.roomeqwizard.com** – we tested V5.20.13. For Mac users, this is a good option. We'll focus on this program as it is the most actively supported.

A surprising but excellent option for Windows users is 'Speaker Workshop', which has been around for over 20 years. It is dedicated to designing and building loudspeakers and, among other things, can measure Thiele-Small parameters accurately and simply.

Features and Specifications

- Measures loudspeaker driver frequency and phase responses
- Measures loudspeaker relative SPL (absolute SPL possible with external calibration sources)
- Time alignment of loudspeaker drivers in combination with an oscilloscope
- Measures the impedance of loudspeakers, crossover networks
- Measures the value of capacitors, inductors (µH to mH range) and resistors
- Incorporates a microphone preamplifier and small power amp
- Frequency range: 10Hz to 20kHz (depending on your sound card)
- Power output; about 5W peak into 8Ω (not continuous due to power supply limitations)
- Amplifier gain: switchable between +14dB and +34dB
- Common-mode rejection ratio (CMRR): >60dB on prototype (20Hz to 20kHz)
- THD+N: <0.01% across the audio range
- 50/100Hz hum: more than 100dB below full-scale
- Microphone phantom power: 48V, selectable via header on PCB
- Power supply: 15V AC @ 1.2A from a plugpack (no mains wiring)

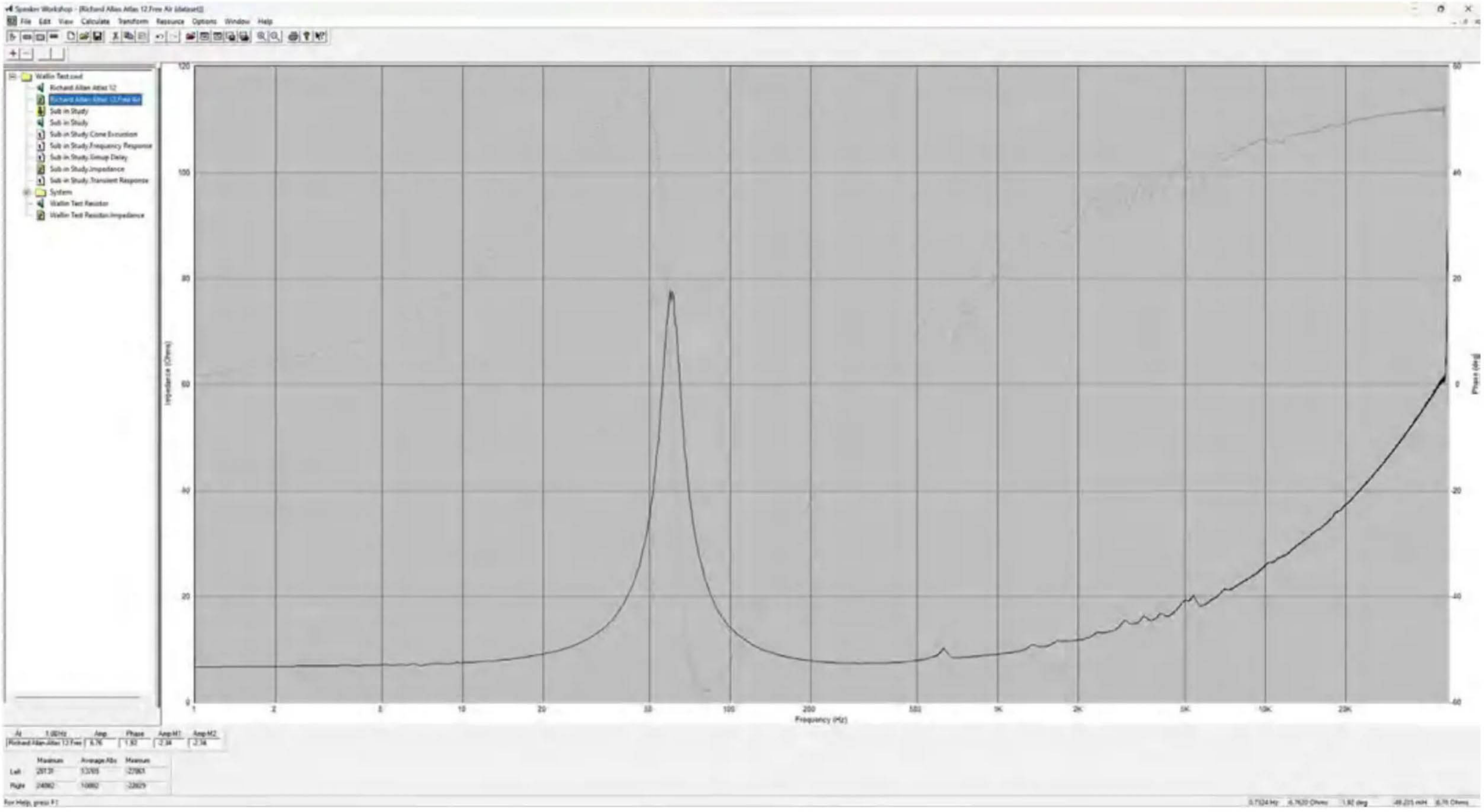

Speaker Workshop - [Richard Allan Atlas 12.Free Air (dataset)]
File
Edit
View
Calculate
Transform
Resource
Options
Window
Help
Wallin Test.swd
Richard Allan Atlas 12
Sub in Study
Sub in Study
Sub in Study.Cone Excursion
Sub in Study.Frequency Response
Sub in Study.Group Delay
Sub in Study.Impedance
Sub in Study.Transient Response
System
Wallin Test Resistor
Wallin Test Resistor.Impedance
120
100
80
60
40
20
0
Impedance (Ohms)
1
2
5
10
20
50
100
200
500
1K
2K
5K
10K
20K
Frequency (Hz)
Phase (deg)
For Help, press F1

Fig.1: the magnitude and phase of the impedance of a loudspeaker bass driver in free air. You can see the high impedance peak close to 80Ω at 60Hz and the rapid change in phase around there.

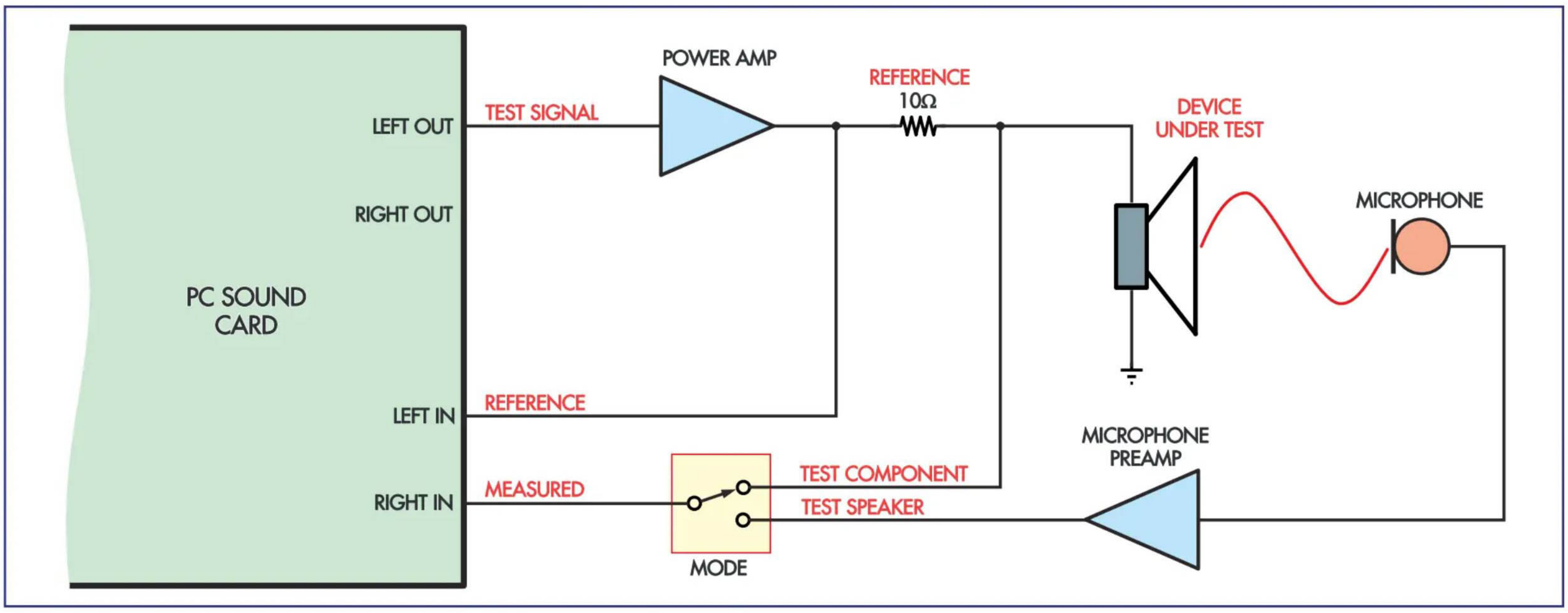

PC SOUND CARD
LEFT OUT
RIGHT OUT
LEFT IN
RIGHT IN
TEST SIGNAL
POWER AMP
REFERENCE 10Ω
DEVICE UNDER TEST
MICROPHONE
REFERENCE
MICROPHONE PREAMP
MEASURED
TEST COMPONENT
TEST SPEAKER
MODE

Fig.2: the basic arrangement for measuring impedance. Conventionally, the power amplifier and microphone preamplifier are standalone devices, wired to the 'Wallin Jig'. Our new design incorporates everything you need into one, handy, compact unit.

Sadly, it hasn't been upgraded since about 2001. Even though it gives a warning message on startup, this remains a brilliant tool and is worth checking out. The last version is V1.06 and is available from the download page at: **www.claudionegro.com**

These programs perform measurements in slightly different ways but ultimately deliver similar results. REW uses a swept sinewave to make measurements, while Speaker Workshop uses a noise pulse. Both programs perform Fourier transforms and compare the reference to the measured signals to calculate either the speaker frequency response or the impedance of the DUT.

Our *Loudspeaker Test Jig* provides the amplification and switching to allow these programs to work. We have kept it as simple as practical. It would be possible to add more switching for attenuators and reference resistors, but as we will show in the 'how to use this' article, they would be gilding the lily and make it harder to use than necessary. You could easily add more switching externally if you wish.

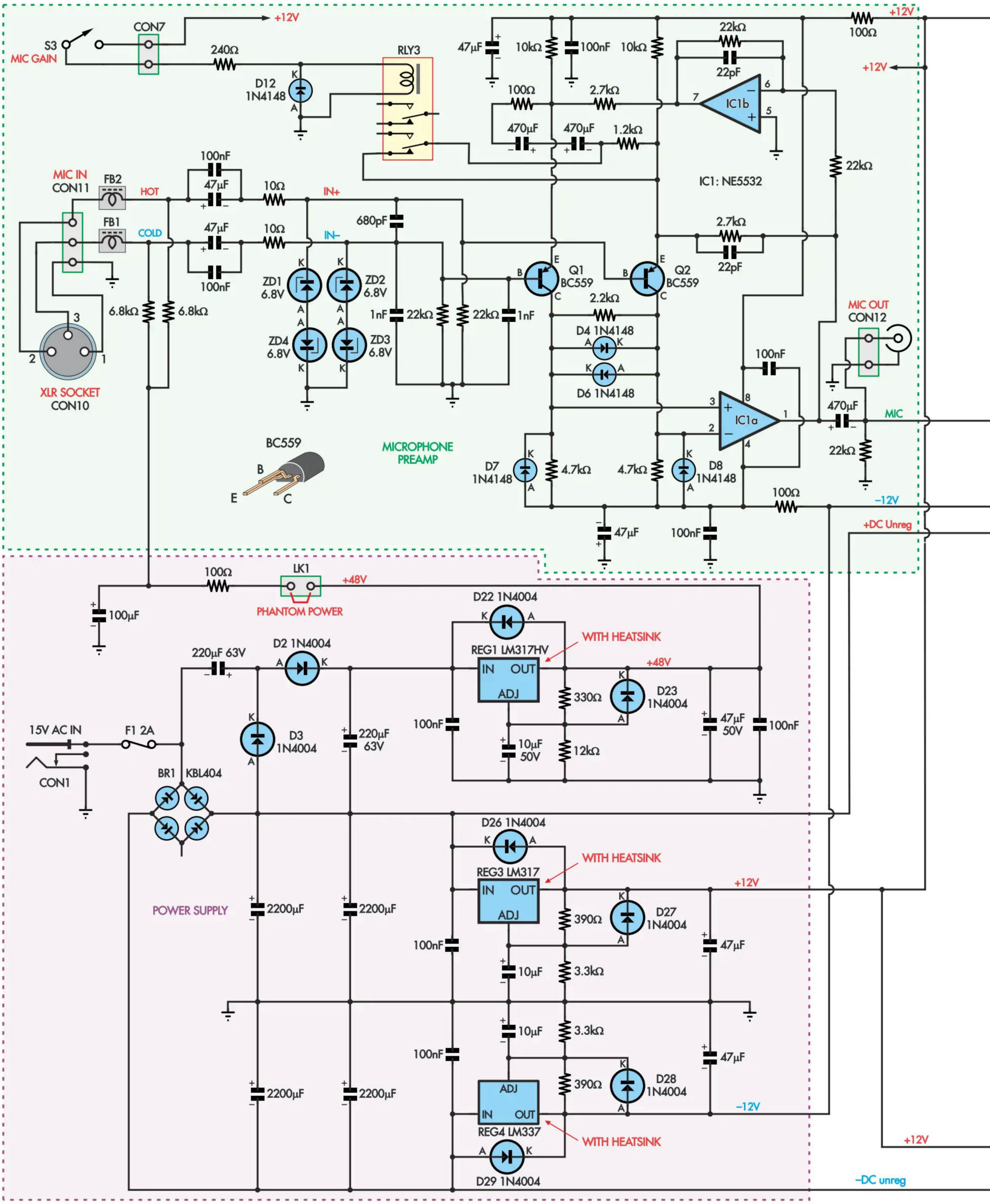
Microphone selection

As for the microphone, you need a measurement microphone. The Shure SM58 has a shaped frequency response and is unsuitable for this job. At the low end, you can buy a Behringer ECM8000 for about £30 or a Dayton Audio EMM6 with calibration data for about £80. Alternatively, it is easy to build an excellent measurement mic very cheaply indeed, which will be the subject of an upcoming project.

Circuit description

The full circuit is shown in Fig.3, and it has five main sections: the power amplifier, microphone preamplifier, input buffer, switching and power supply, shown as shaded areas.

While some of these sections connect to each other, besides the power supply, they primarily operate as independent blocks. The power amplifier is used to drive the loudspeaker being tested, while the microphone preamplifier picks up the radiated sound and converts it to a signal that can be analysed. The input buffer allows the


S3
MIC GAIN
CON7
+12V
240Ω
RLY3
D12
1N4148
K
A
47µF
10kΩ
100nF
10kΩ
22kΩ
22pF
100Ω
+12V
+12V
100Ω
2.7kΩ
IC1b
7
6
5
470µF
470µF
1.2kΩ
22kΩ
IC1: NE5532
MIC IN
CON11
FB2
HOT
FB1
COLD
100nF
47µF
10Ω
IN+
47µF
10Ω
IN–
680pF
100nF
2.7kΩ
22pF
ZD1
6.8V
ZD2
6.8V
ZD4
6.8V
ZD3
6.8V
1nF
22kΩ
22kΩ
1nF
Q1
BC559
Q2
BC559
B
E
C
2.2kΩ
D4 1N4148
D6 1N4148
6.8kΩ
6.8kΩ
XLR SOCKET
CON10
MIC OUT
CON12
100nF
IC1a
3
2
8
4
1
470µF
MIC
22kΩ
BC559
MICROPHONE PREAMP
D7
1N4148
4.7kΩ
4.7kΩ
D8
1N4148
100Ω
–12V
+DC Unreg
47µF
100nF
100Ω
LK1
+48V
PHANTOM POWER
100µF
D22 1N4004
WITH HEATSINK
REG1 LM317HV
IN
OUT
ADJ
+48V
220µF 63V
D2 1N4004
330Ω
D23
1N4004
100nF
47µF
50V
100nF
15V AC IN
F1 2A
D3
1N4004
220µF
63V
10µF
50V
12kΩ
CON1
BR1
KBL404
D26 1N4004
WITH HEATSINK
REG3 LM317
+12V
390Ω
D27
1N4004
POWER SUPPLY
2200µF
2200µF
100nF
47µF
10µF
3.3kΩ
10µF
3.3kΩ
100nF
47µF
2200µF
2200µF
390Ω
D28
1N4004
–12V
REG4 LM337
WITH HEATSINK
+12V
D29 1N4004
–DC unreg

Loudspeaker Test Jig

sound card's outputs to be monitored while one is fed to the power amplifier.

The switching section determines whether the output of the mic preamp or sense input is fed to the computer sound card's inputs. It also provides switchable attenuation for the sense input and switchable gain for the amplifier.

Power amplifier

We don't need a substantial power amplifier; the LM1875 IC is commonly available and requires minimal parts to work. It needs to be able to drive a loudspeaker at a modest volume and be tolerant of abuse, which can happen with this sort of equipment. You would never short the amplifier, would you?

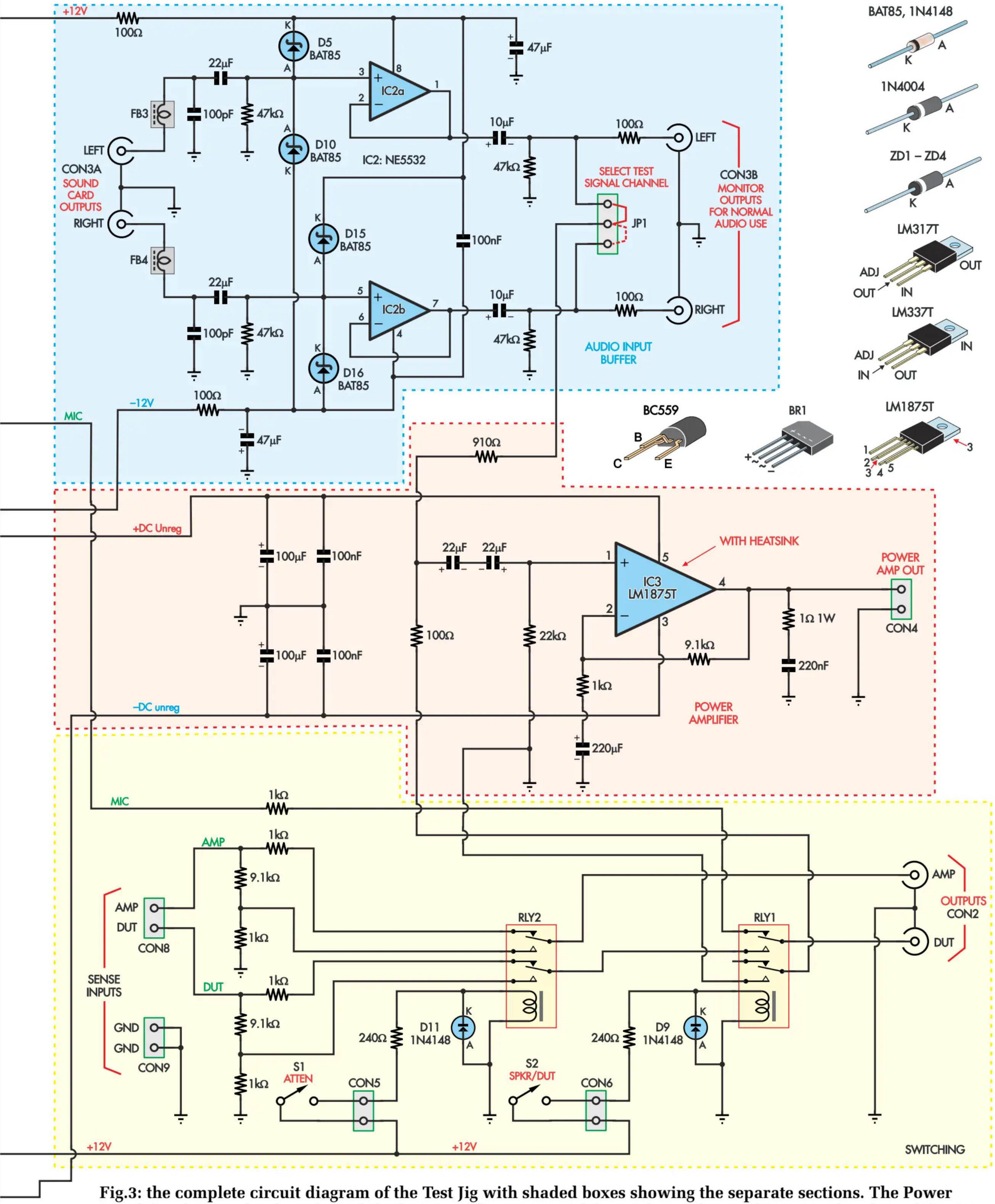

+12V
100Ω
D5
BAT85
K
A
22μF
3
8
IC2a
1
2
47μF
FB3
100pF
47kΩ
D10
BAT85
10μF
100Ω
LEFT
IC2: NE5532
47kΩ
SELECT TEST SIGNAL CHANNEL
JP1
CON3B
MONITOR OUTPUTS FOR NORMAL AUDIO USE
LEFT
CON3A
SOUND CARD OUTPUTS
RIGHT
D15
BAT85
100nF
FB4
22μF
5
IC2b
7
6
4
10μF
100Ω
RIGHT
100pF
47kΩ
D16
BAT85
47kΩ
AUDIO INPUT BUFFER
MIC
−12V
100Ω
47μF
910Ω
+DC Unreg
100μF
100nF
100μF
100nF
22μF
22μF
WITH HEATSINK
IC3
LM1875T
POWER AMP OUT
1Ω 1W
CON4
100Ω
22kΩ
9.1kΩ
220nF
1kΩ
POWER AMPLIFIER
−DC unreg
220μF
MIC
1kΩ
AMP
1kΩ
9.1kΩ
AMP
DUT
CON8
1kΩ
RLY2
RLY1
AMP
OUTPUTS
CON2
DUT
SENSE INPUTS
DUT
1kΩ
9.1kΩ
240Ω
D11
1N4148
240Ω
D9
1N4148
GND
GND
CON9
1kΩ
S1
ATTEN
CON5
S2
SPKR/DUT
CON6
+12V
+12V
SWITCHING
BAT85, 1N4148
1N4004
ZD1 – ZD4
LM317T
ADJ
OUT
IN
OUT
LM337T
ADJ
IN
OUT
IN
BC559
B
C
E
BR1
LM1875T
1
2
3
4
5
3

Fig.3: the complete circuit diagram of the Test Jig with shaded boxes showing the separate sections. The Power Amplifier drives a loudspeaker while the Microphone Preamplifier picks up the resulting sound and amplifies it to send it to the sound card. The Speaker Measurement section is essentially a buffer, while the Switching section lets you perform various tests without disconnecting and reconnecting many leads.

We run it from dual half-wave rectified 15V AC to get positive and negative rails of about ±20V from the 15V AC plugpack. This is cheeky, but we only need a couple of watts at most. Note that only half the diodes in bridge rectifier BR1 are used since we don't have a centre-tapped transformer (few plugpacks have a centre tap as it requires a 3-pin connector).

This power amplifier will provide sufficient output to allow you to wire your speaker to the output binding posts to perform listening tests as you develop it. We have set the gain to about 10 (set by the ratios of the 9.1kΩ and 1kΩ resistors), which is low but enough for our purposes.

Parts List – Loudspeaker Test Jig

1 double-sided PCB coded 04106231, 99.5 × 189.5mm
1 Hammond 220×103×53mm black aluminium instrument case **[element14 9287892, Mouser 546-1455N2201BK, Digi-Key HM1732-ND]**
1 15V AC plugpack (rated at least 1.2A) **[Jaycar MP3021]**
3 2A 5V DC coil DPDT PCB-mounting telecom relays (RLY1-RLY3) **[Altronics S4128B]**
4 5mm-long, 2mm inner diameter ferrite beads (FB1-FB4)
2 PCB-mounting M205 fuse clips (F1)
1 2.1mm or 2.5mm inner diameter PCB-mounting DC barrel socket, to suit plugpack (CON1)
1 stereo right-angle PCB-mounting RCA socket, above/below (CON2) **[Altronics P0210]**
1 dual stereo vertical PCB-mounting RCA socket (CON3) **[Altronics P0214]**
7 2-way 2.54mm right-angle polarised headers with matching plugs (CON4-CON9, CON12) **[Altronics P5512 + P5472 + P5470A × 2]**
1 3-way 2.54mm right-angle polarised header with matching plug (CON11) **[Altronics P5513 + P5473 + P5470A × 2]**
1 2-pin header with jumper shunt (LK1)
1 3-pin header with jumper shunt (JP1)
2 8-pin DIL sockets (**optional**; for IC1 and IC2)
2 dual panel-mount red/black binding posts with banana sockets **[Altronics P9257A]**
3 SPDT solder tail panel-mount toggle switches with locking mechanism **[Altronics S1311]**
1 panel-mount 3-pin XLR socket for microphone (CON10) **[Altronics P0903]**

Hardware and wire
1 2A 250V M205 fast-blow fuse (F1)
1 84×24×28mm low-profile PCB-mounting heatsink **[Altronics H0668]**
3 16×22mm TO-220 PCB-mounting heatsinks **[Altronics H0650]**
5 TO-220 insulating kits (washers + bushes) **[Altronics H7210, set of four]**
1 M3 × 25mm panhead machine screw
6 M3 × 16mm panhead machine screws
6 M3 shakeproof washers
6 M3 flat washers
4 M3 hex nuts
2 fibre or Nylon washer, 3mm inner diameter **[Jaycar HP0148]**
2 4G × 12mm countersunk head machine screws **[Bunnings 2420062]**
1 150mm length of 3-wire jumper cable
1 300mm length of green light-duty hookup wire
1 1m length of light-duty figure-8 twin lead or ribbon cable
1 200mm length of 3mm diameter black heatshrink tubing

Semiconductors
2 NE5532 dual low-noise op amps, DIP-8 (IC1, IC2)
1 LM1875T 20W audio amplifier, TO-220-5 (IC3) **[Jaycar ZL3755]**
1 LM317HV high-voltage adjustable linear regulator, TO-220 (REG1) **[Altronics Z0545]**
1 LM317 adjustable positive linear regulator, TO-220 (REG3)
1 LM337 adj. negative linear regulator, TO-220 (REG4)
2 BC559 100mA 30V PNP transistors, TO-92 (Q1, Q2)
4 6.8V 1W zener diodes (ZD1-ZD4)
1 400V 4A SIL bridge rectifier (BR1) **[eg, KBL404; Altronics Z0076A]**
8 1N4004 400V 1A diodes (D2, D3, D22, D23, D26-D29)
7 1N4148 75V 200mA signal diodes (D4, D6-D9, D11, D12)
4 BAT85 30V 200mA schottky diodes (D5, D10, D15, D16)

Capacitors
4 2200µF 25V low-ESR radial electro, 7.5mm pitch **[Altronics R6204; Jaycar RE6330]**
3 470µF 25V radial electrolytic, 5mm pitch **[Altronics R5164; Jaycar RE6326]**
2 220µF 63V radial electrolytic, 5mm pitch **[Altronics R5148; Jaycar RE6348]**
1 220µF 16V radial electrolytic, 3.5mm pitch **[Altronics R5143; Jaycar RE6312]**
3 100µF 50V radial electrolytic, 5mm pitch **[Altronics R6127; Jaycar RE6346]**
9 47µF 50V low-ESR radial electrolytic, 3.5mm pitch **[Altronics R6107; Jaycar RE6344]**
2 22µF 50V low-ESR radial electrolytic, 2.5mm pitch **[Altronics R6077; Jaycar RE6342]**
2 22µF 50V non-polarised radial electrolytic, 3.5mm pitch **[Altronics R6570A; Jaycar RY6816]**
5 10µF 50V low-ESR radial electrolytic, 2.5mm pitch **[Altronics R6067; Jaycar RE6075]**
1 220nF 63V MKT polyester
12 100nF 63V MKT polyester
2 1nF 63V MKT polyester
1 680pF 50V NP0/C0G or YSP radial ceramic
2 100pF 50V NP0/C0G or SL radial ceramic
2 22pF 50V NP0/C0G radial ceramic

Resistors *(all ¼W 1% axial unless otherwise stated)*
4 47kΩ
6 22kΩ
1 12kΩ
2 10kΩ
3 9.1kΩ
2 6.8kΩ 0.5W or 0.6W 1%
2 4.7kΩ
2 3.3kΩ
2 2.7kΩ
1 2.2kΩ
1 1.2kΩ
6 1kΩ
1 910Ω
2 390Ω
1 330Ω
3 240Ω
9 100Ω
2 10Ω
1 10Ω 5W 5% non-inductive **[Altronics R0323; Jaycar RR3250]**
1 1Ω 1W 5%

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The signal is AC-coupled to IC3's input via a pair of back-to-back 22µF electrolytic capacitors to remove any DC bias. The output goes straight to CON4, which is wired to a pair of binding posts. The 1Ω/220nF Zobel network ensures stability.

We mount the LM1875 on a heatsink to ensure that the IC has adequate cooling if you do extended testing. This heatsink is available from Altronics, but if you can't find that, a folded piece of aluminium would work just fine.

Interestingly, the Altronics heatsink we bought had one hole in the middle, but their specification has two holes, and our design accommodates that. If yours only comes with one hole as well, you will need to drill a 3mm hole 10mm to the left of the centre.

Microphone preamp

This basic design is pretty standard across the audio industry. It includes a tweak by Douglas Self, described in his books, whereby the input transistors are included in the operational amplifier feedback loop. This significantly reduces the resulting distortion.

The microphone preamplifier is simply an AC-coupled balanced amplifier with switchable gain. If you switch off the phantom power, this becomes a simple balanced input. That is handy to remember if you want to probe a circuit using the *Loudspeaker Test Jig*.

RF is filtered out of the input signals by series ferrite beads and an RC low-pass filter comprising 10Ω resistors and 680pF and 1nF capacitors. 48V phantom power, if selected, is applied via 6.8kΩ resistors, with a 1kΩ/100µF low-pass filter before them to remove any supply noise. Pairs of back-to-back zener diodes protect the rest of the circuitry from any voltage spikes that might be picked up.

The two balanced signals are then fed to the bases of PNP transistors Q1 and Q2, which are within the feedback loop of low-noise op amps IC1a and IC1b, providing the amplification as follows.

Pins 2 and 3 of IC1a must be at essentially the same voltage, enforced by negative feedback from this op amp. The current through transistors Q1 and Q2 will be essentially the same, and within the tolerance of transistor matching, their emitter voltages will be the same.

From a DC perspective, the output will be close to 0V as IC1b inverts the signal from IC1a, creating differential feedback to the transistors. The transistor bases are AC-coupled to the input and DC-biased to ground, so their emitters will be pulled up to about 0.6V by the 10kΩ emitter resistors and the 2.7kΩ op amp feedback resistors.

Q1 and Q2 will each pass about 1mA, which will primarily flow through the 4.7kΩ collector resistors, resulting in pins 2 and 3 of IC1a being about 4V above the negative rail.

The AC input is a differential voltage between the bases of Q1 and Q2. The emitters of Q1 and Q2 are the feedback point, via the 2.7kΩ resistors. As the input is differential, the 100Ω resistor (and 1.2kΩ if the contacts of relay RLY3 are not shorting it out) see the total differential voltage; the midpoint of these can be seen as a 'virtual zero point'.

So the gain is defined by the 2.7kΩ feedback resistors with the parallel combination of half of (100Ω + 1.2kΩ) and (10kΩ + 10kΩ) forming the voltage divider for gain.

Gain is controlled by the 2.7kΩ resistors in series with the NE5532 outputs, combined with the 10kΩ resistors to the positive rail and the 1.2kΩ and 100Ω resistors. A 20dB gain step is implemented by switching RLY3 across the 1.2kΩ resistor.

The gain on the low setting can be calculated as:

$$
\begin{aligned}
&1 + (2.7\text{k}\Omega \div (10\text{k}\Omega \parallel [(1.2\text{k}\Omega + 100\Omega) \div 2]))\\
&= 1 + (2700\Omega \div 610\Omega)\\
&= 5.42 \text{ times gain } (+14.7\text{dB})
\end{aligned}
$$

On the high setting, it is:

$$
\begin{aligned}
&1 + (2.7\text{k}\Omega \div (10\text{k}\Omega \parallel [100\Omega \div 2]))\\
&= 1 + (2700\Omega \div 49.8\Omega)\\
&= 55.2 \text{ times gain } (+34.8\text{dB})
\end{aligned}
$$

The input buffer

The *Loudspeaker Test Jig* includes a simple op-amp-based buffer to ensure that your sound card output is presented with a high impedance, while also providing a monitor output to drive an amplifier or other equipment. You can even use this output to drive an active crossover for testing active speakers.

The input includes protection against RF noise with ferrite beads and 100pF capacitors to ground, while schottky clamp diodes protect the op amp from voltage spikes on the input.

The signals are AC-coupled to the op amp inputs via 22µF non-polarised capacitors with 47kΩ DC bias resistors, forming a high-pass filter with a -3dB point of 0.15Hz. So there will be no detectable roll-off at 20Hz. The outputs are also AC-coupled and have 100Ω series resistors for stability and safety.

A jumper on JP1 can feed either the left or right channel to the input of the power amplifier.

Switching section

This section does two main things in the *Loudspeaker Test Jig*. It switches one of the sound card's input channels between the output of the microphone preamplifier and a 'DUT Sense' input. It also allows you to select a gain of 1× or 0.1× for both the 'DUT Sense' signal and 'Amp Out Sense' signal.

When 'DUT Sense' is selected as the signal source, the power amplifier gain is automatically cut from 10× to 1× by switching in a 910Ω/100Ω resistive attenuator in its input signal path. This is so that when testing components a signal of only a few hundred millivolts is applied to them. That allows you to measure the impedance of tweeters without over-driving them.

Despite this, if you are testing tweeter responses, always put a 20-100µF capacitor in series with the tweeter to avoid over-driving it at low frequencies.

When testing loudspeaker frequency responses, though, you need more volume. Therefore, with the 10× gain provided in the amplifier, it delivers a couple of volts RMS (depending on where you set your sound card volume). This will be loud enough to get good frequency response plots.

Power supply

The power supply for the *Loudspeaker Test Jig* is minimalist to keep cost,

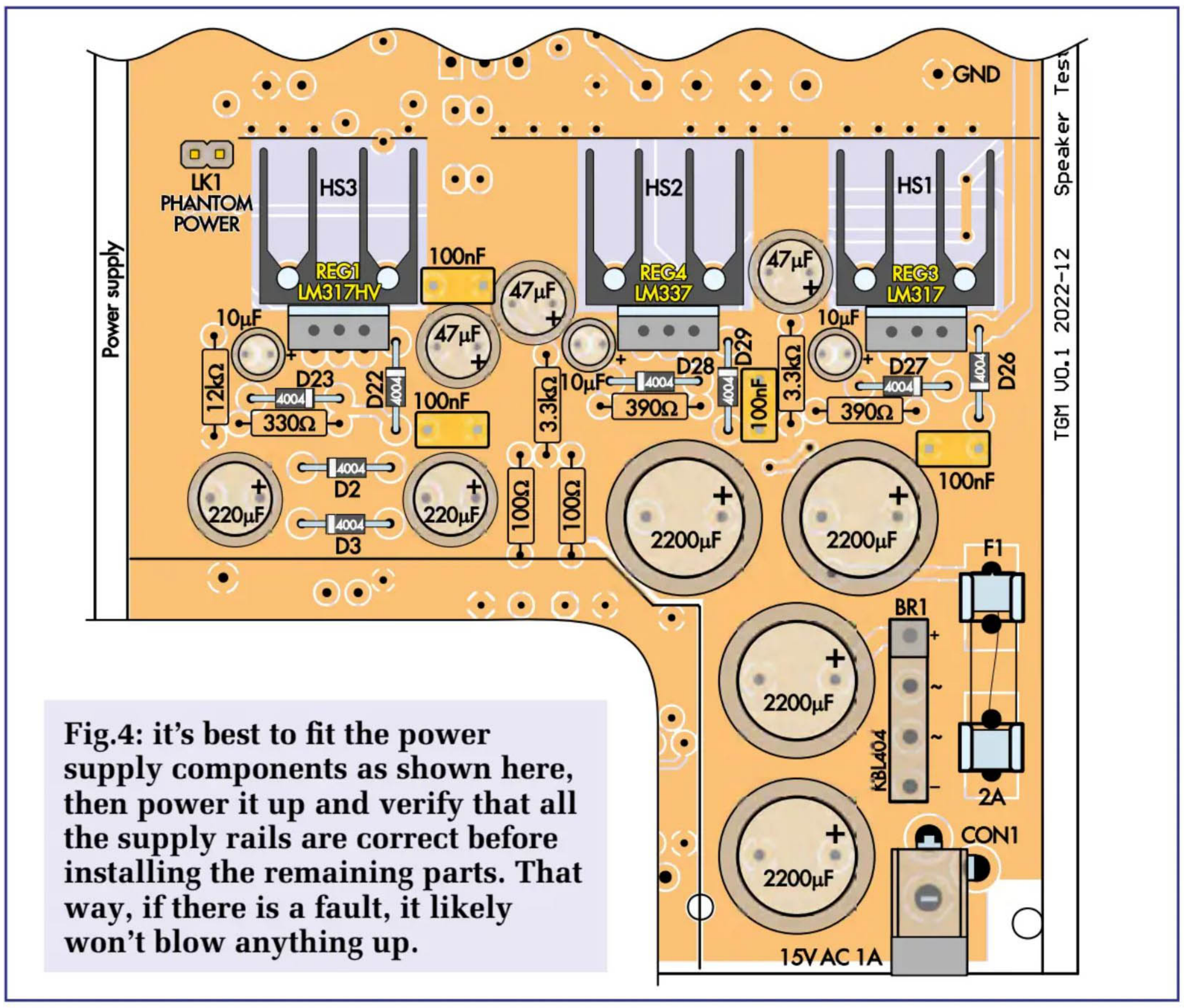


Fig.4: it's best to fit the power supply components as shown here, then power it up and verify that all the supply rails are correct before installing the remaining parts. That way, if there is a fault, it likely won't blow anything up.

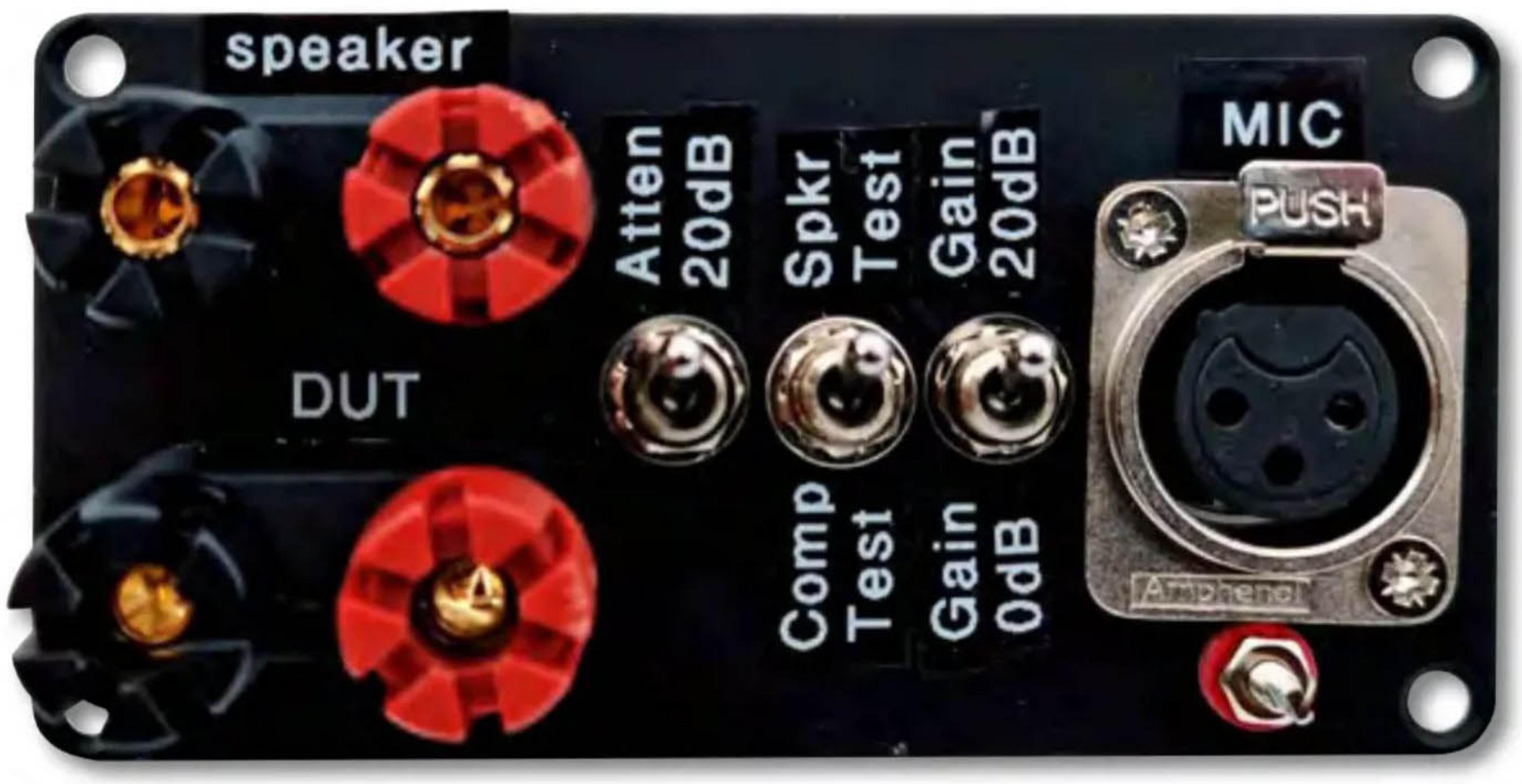

speaker
DUT
Atten 20dB
Spkr Test
Gain 20dB
MIC
PUSH
Comp Test
Gain 0dB
Amphenol

Photo 1: an exterior view of the completed front panel assembly. Dymo labels will help you to remember what each switch and terminal does down the track!

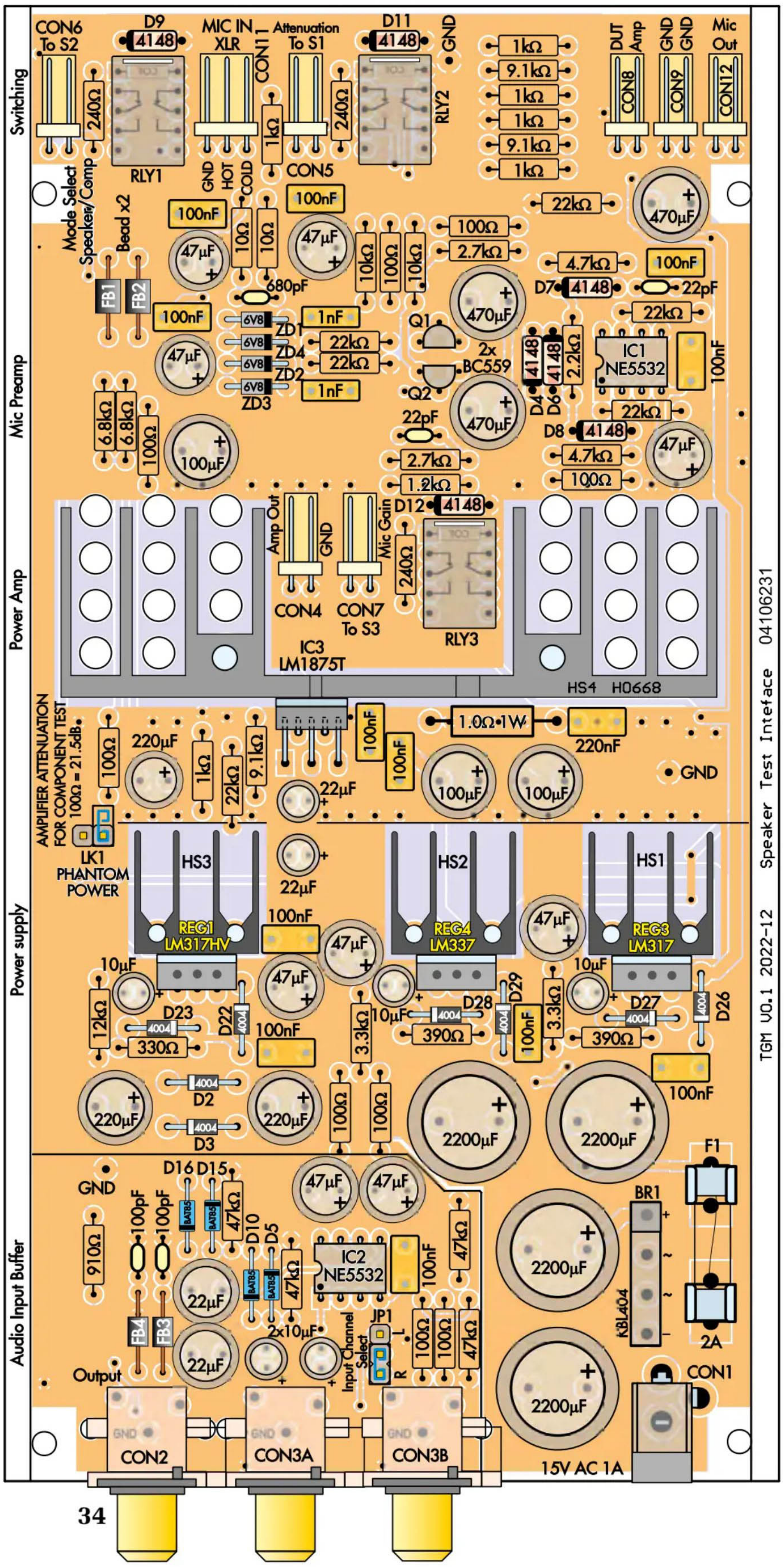

Switching
Mode Select Speaker/Comp
Mic Preamp
Power Amp
AMPLIFIER ATTENUATION FOR COMPONENT TEST 100Ω = 21.5dB
Power supply
Audio Input Buffer
CON6 To S2
RLY1
MIC IN XLR
CON11
Attenuation To S1
GND HOT COLD
CON5
RLY2
DUT Amp
CON8
CON9
Mic Out
CON12
Bead x2
FB1
FB2
ZD1
ZD2
ZD3
ZD4
Q1
Q2
2x BC559
IC1 NE5532
Amp Out
Mic Gain
CON4
CON7 To S3
RLY3
IC3 LM1875T
HS4 H0668
LK1 PHANTOM POWER
HS3
HS2
HS1
REG1 LM317HV
REG4 LM337
REG3 LM317
F1
BR1
KBL404
2A
CON1
15V AC 1A
IC2 NE5532
JP1
Input Channel Select
Output
CON2
CON3A
CON3B
04106231
Speaker Test Inteface
TGM V0.1 2022-12

Fig.5: once you've tested the power supply, you can fit all the components as shown here. Ensure all the TO-220 devices are insulated from their heatsinks and watch the polarity of the ICs, diodes and electrolytic capacitors. Two of the 22µF electrolytics are non-polarised types (near the lower-left corner), so no polarity markings are shown.

complexity and size down. We use a single 15V AC plugpack to power the unit. As mentioned earlier, dual half-wave rectification via BR1 provides the split rails to drive the power amplifier. This avoids the need for any fancy voltage inverting IC or the use of a single-rail topology for the whole *Test Jig*.

It does mean that our supply rails are 50Hz half-wave rectified, with resultant ripple challenges. So we have doubled down on the filter capacitors and used two 2200µF capacitors per rail, which in a standard application, would be overkill. In this case, a couple of pounds worth of extra capacitors saves on using a dual-winding transformer.

With 4400µF per rail, there will only be a couple of volts ripple on the rails during higher-power tests.

The small-signal circuitry needs clean power, so we have added LM317/337 regulators generating regulated rails at nominally ±12V. These are textbook circuits.

Generating the 48V phantom power rail for the measurement microphone is a little more interesting. We use a voltage doubler circuit that steals energy from the positive unfiltered rail via diode D3 charging the 220µF capacitor at its cathode on negative voltage swings at the plugpack tip, then dumping its charge into the other 220µF capacitor via D2 on positive swings.

The second 220µF capacitor 'sits on top of' the main unfiltered rail, resulting in close to 70V DC at the cathode of D2 when it is unloaded. This is dropped to 48V by an LM317HV adjustable regulator. You could use a normal LM317, provided you never short its output to ground. In typical operation, its output goes via a 1kΩ resistor, so there is no chance of that happening in daily use.

The current drawn from the 48V rail is never more than 14mA, so the 220µF capacitors are more than sufficient to keep ripple below 1V.

We placed heatsinks on all regulators, but didn't notice them getting that warm. If you want to save a little expense, you might get away without using them.

Construction

Construction is fairly easy, although, for designs like this, we like to load the power supply section first and check the voltage rails. Once that checks out, you can power it down and fit all the remaining parts with the confidence that a power supply fault won't fry them at switch-on!

The *Loudspeaker Test Jig* is built on a 99.5 × 189.5mm double-sided PCB coded 04106231, available from the *PE PCB Service*.

To build the power supply section, fit all the resistors and diodes in that section, as shown in Fig.4. Be careful with the orientation of the diodes as they vary. Follow with the MKT and electrolytic capacitors in this section (watching the polarity of the electrolytics), then the rectifier, fuse holder and connectors. Install a 2A fuse.

Finally, attach the regulators to the heatsinks with a TO-220 insulator kit on each. Don't tighten the screws until you have inserted the regulators with their heatsinks into the PCB. Then you can solder the heatsink mounting pins along with the regulator pins.

Testing the power supply

Plug in the 15V AC plugpack and check the unregulated rails by measuring the voltages on pins 3 and 5 of the LM1875 IC relative to GND (there is a GND test point at upper left in the Audio Input Buffer section). These voltages ought to be 18-24V DC. If they measure low, check the AC voltage and verify that the bridge rectifier has been installed the right way around. Also check the capacitor orientations.

Assuming that's OK, measure the ±12V rails at pin 2 of the LM317 (REG3) and pin 3 of the LM337 (REG4). These ought to be within 1V. If not, verify that the regulators are in the right spots, the correct resistors have been used and the diodes are oriented properly. There should always be 1.25V between the ADJ and OUT pins of the LM3X7s.

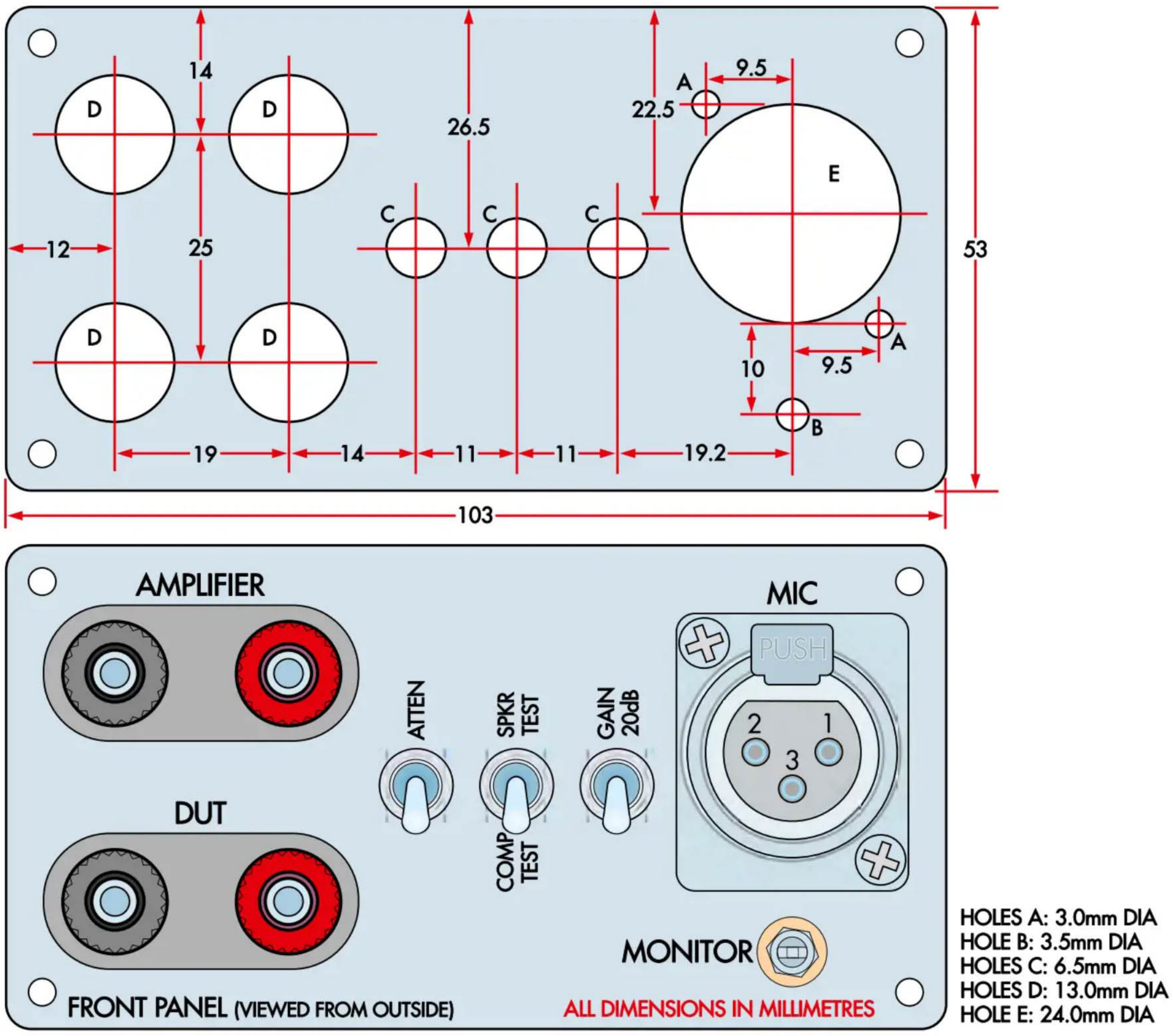
Next, check that the 48V rail is within 3V (ie, 45-51V). This is accessible on pin 2 of the LM317HV. If it is off, verify that the input voltage on its pin 3 is well above 48V. Also check the resistor values around this regulator and that the capacitors and diodes are the right way around.

Finishing off the PCB

Now that we know the power supply is working, remove power and fit all the remaining parts, as shown in Fig.5. As usual, start with the lower-profile components by mounting the resistors, diodes, relays, NE5532 ICs and right-angle headers first. Then move on to the larger parts, including the capacitors and RCA sockets.

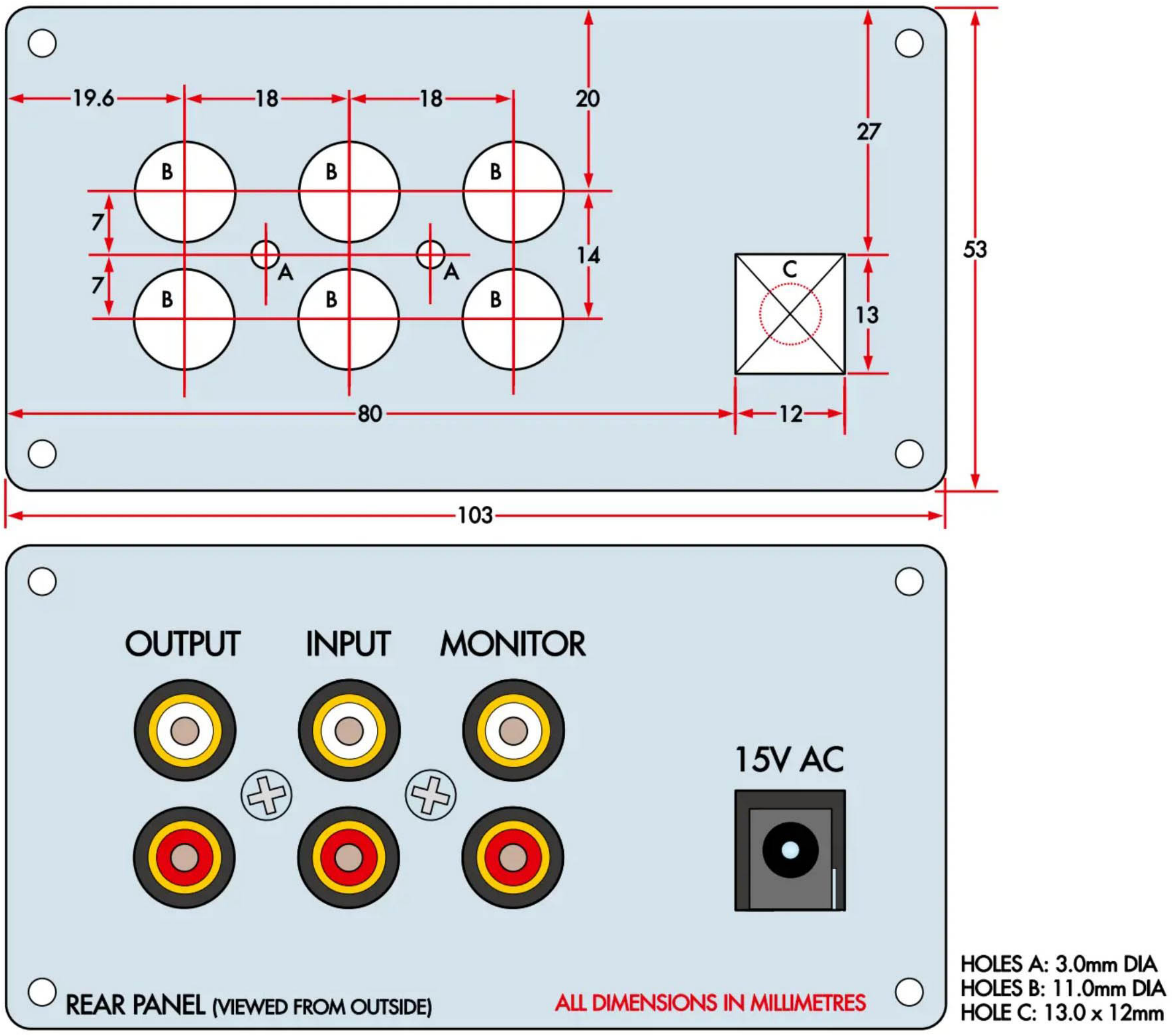
As with the regulators, loosely attach the LM1875 to the large heatsink and use an insulating kit. Insert the IC into its pads and solder the heatsink to the board. The solder pins will require some effort to get hot enough, but they do work (it is not screwed to the PCB). Once it is held in place securely, tighten up the IC mounting screw and solder its leads.

Note that there are two bipolar (non-polarised) electrolytic capacitors right next to CON2, as we don't know if an input will have a DC offset. They have polarity marks on the PCB, but



D
D
D
D
C
C
C
E
A
A
B
14
25
12
19
14
11
11
19.2
26.5
22.5
9.5
9.5
10
53
103
AMPLIFIER
DUT
ATTEN
SPKR TEST
COMP TEST
GAIN 20dB
MIC
PUSH
2
1
3
MONITOR
FRONT PANEL (VIEWED FROM OUTSIDE)
ALL DIMENSIONS IN MILLIMETRES
HOLES A: 3.0mm DIA
HOLE B: 3.5mm DIA
HOLES C: 6.5mm DIA
HOLES D: 13.0mm DIA
HOLE E: 24.0mm DIA

Fig.6: drill the front panel supplied with the recommended case as shown here, making sure the pre-drilled countersunk screw holes face outwards.



B
B
B
B
B
B
A
A
C
19.6
18
18
20
27
7
7
14
13
12
80
53
103
OUTPUT
INPUT
MONITOR
15V AC
REAR PANEL (VIEWED FROM OUTSIDE)
ALL DIMENSIONS IN MILLIMETRES
HOLES A: 3.0mm DIA
HOLES B: 11.0mm DIA
HOLE C: 13.0 x 12mm

Fig.7: drill the rear panel as shown here, again paying attention to which side has the holes countersunk. For the rectangular hole, you can drill an 11mm hole and then file the corners out. Otherwise, you can drill out the dotted hole marked in red which only leaves enough room for the plug sleeve.

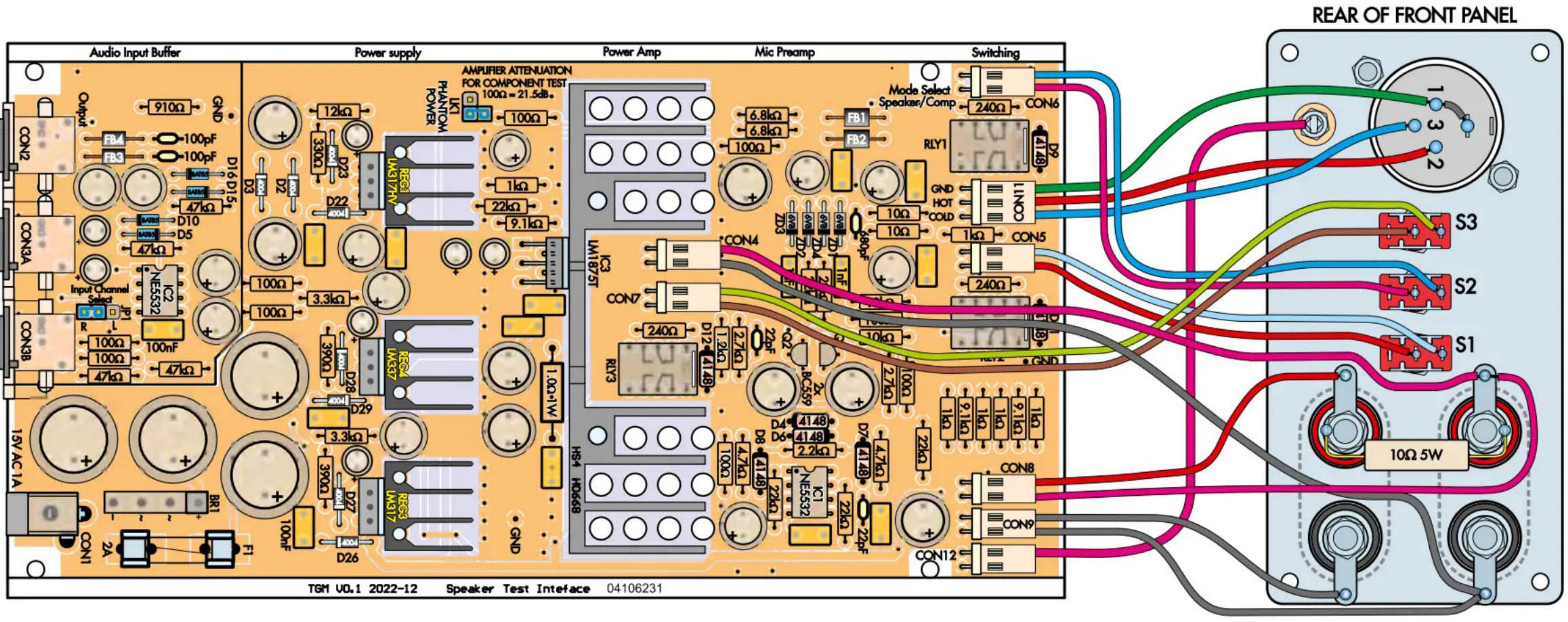

REAR OF FRONT PANEL
Audio Input Buffer
Power supply
Power Amp
Mic Preamp
Switching
AMPLIFIER ATTENUATION FOR COMPONENT TEST 100Ω = 21.5dB
PHANTOM POWER
Mode Select Speaker/Comp
CON1
CON2
CON3A
CON3B
CON4
CON5
CON6
CON7
CON8
CON9
CON10
CON11
CON12
RLY1
RLY3
IC1 NE5532
IC2 NE5532
IC3 LM1875T
HS4 H0668
15V AC 1A
2A
F1
BR1
GND
HOT
COLD
S1
S2
S3
1
2
3
10Ω 5W
TGM V0.1 2022-12 Speaker Test Inteface 04106231

Fig.8: use this diagram and Photos to wire up the front panel. By using polarised header plugs, the whole assembly can be disconnected from the main board, making assembly and disassembly easier.

you can ignore them as the parts are not polarised.

The two 47μF capacitors all the way on the left side of the Mic Preamp section can operate with 48V DC phantom power applied, so we must use at a minimum 50V-rated electrolytic devices and orient them with their longer positive lead to the right as shown. If you will never use phantom power, you could instead use polarised electrolytics with a much lower voltage rating.

With the PCB assembled, we can move on to wiring it up so it can go in the case.

Case preparation

The PCB slides into the second slot up from the bottom in the recommended extruded aluminium case. Use the provided drilling drawings, Figs.6 and 7, to cut the required holes in the front and rear panels. Once prepared, they fit perfectly, allowing you to secure the board using 4G screws through the rear panel into the RCA sockets.

Our recommended case is very tidy, but it is not the cheapest. If you want a more cost-effective solution, any case over about 220mm wide, 130mm deep and more than 60mm high will work. You could consider using plastic instrument cases like Altronics H0476 or H0482; however, you will need to adapt Figs.6 and 7 to fit the differently-sized panels.

The PCB can be secured via spacers and screws through the provided mounting holes if you are not using the recommended case.

Mark and drill the front and rear panels. Be careful to choose the right side of the panel, as the pre-drilled screw holes are countersunk on the outside.

All the holes have been kept circular for easy construction, except the power connector hole, which will require a little filing.

If you choose one of the larger ABS plastic cases, you could spread things out a bit and run flying leads from the power, input and output connectors to the rear panel. However, since the front panel connectors are all wired, you could still mount the PCB right up against the rear panel to avoid extra wiring.

We labelled our panel using Dymo stickers, as shown in Photo 1. We printed labels in small text on 10mm-wide tape and used tweezers to place the labels on the panel. Most of the switches are self-explanatory, but our experience is that we will have forgotten what does what in a year or two. So labelling is a good idea and makes the box look better.

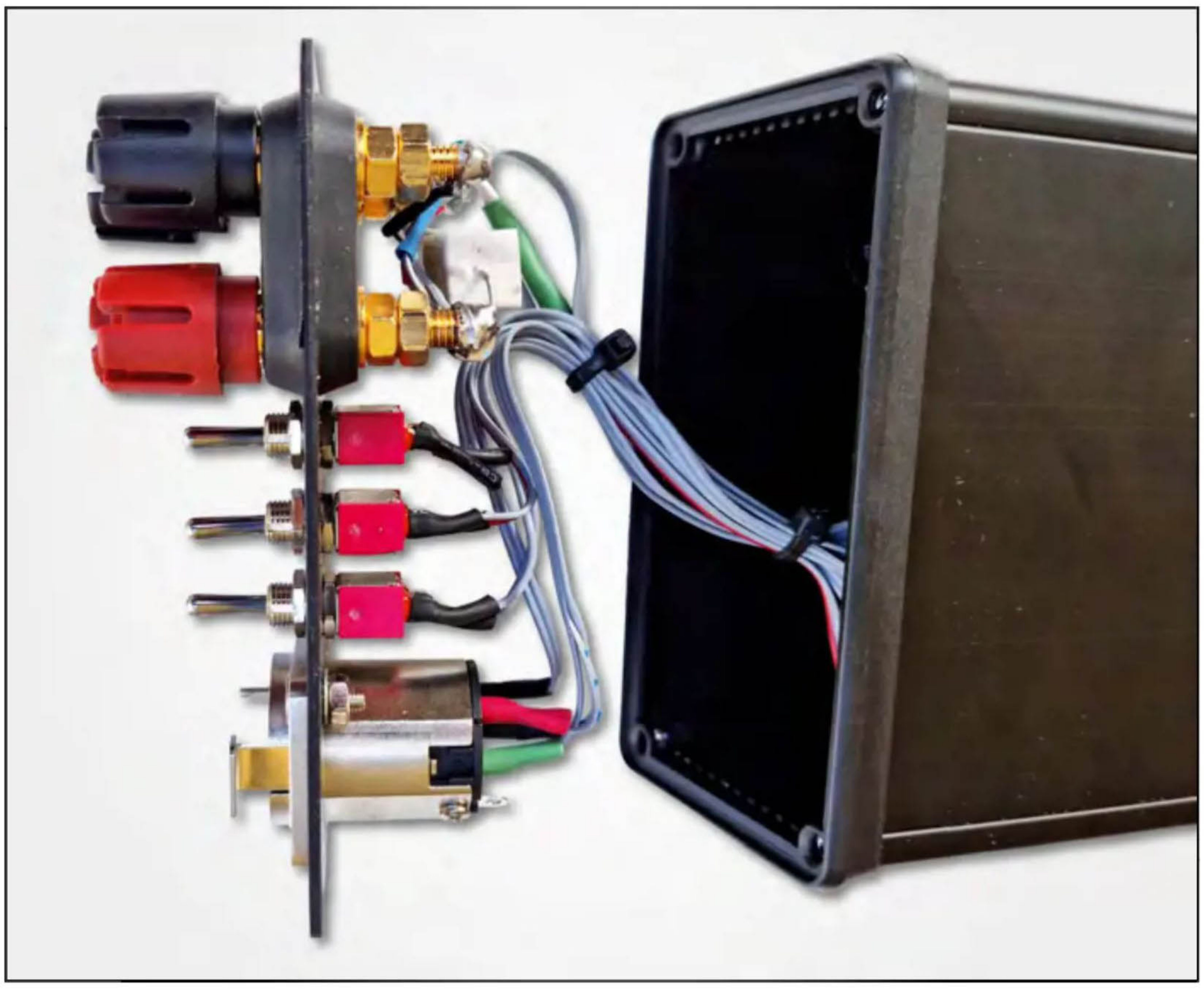


Photo 2: heatshrink tubing and cable ties keep the front panel wiring manageable. Note the 10Ω reference resistor soldered across the binding post terminals.

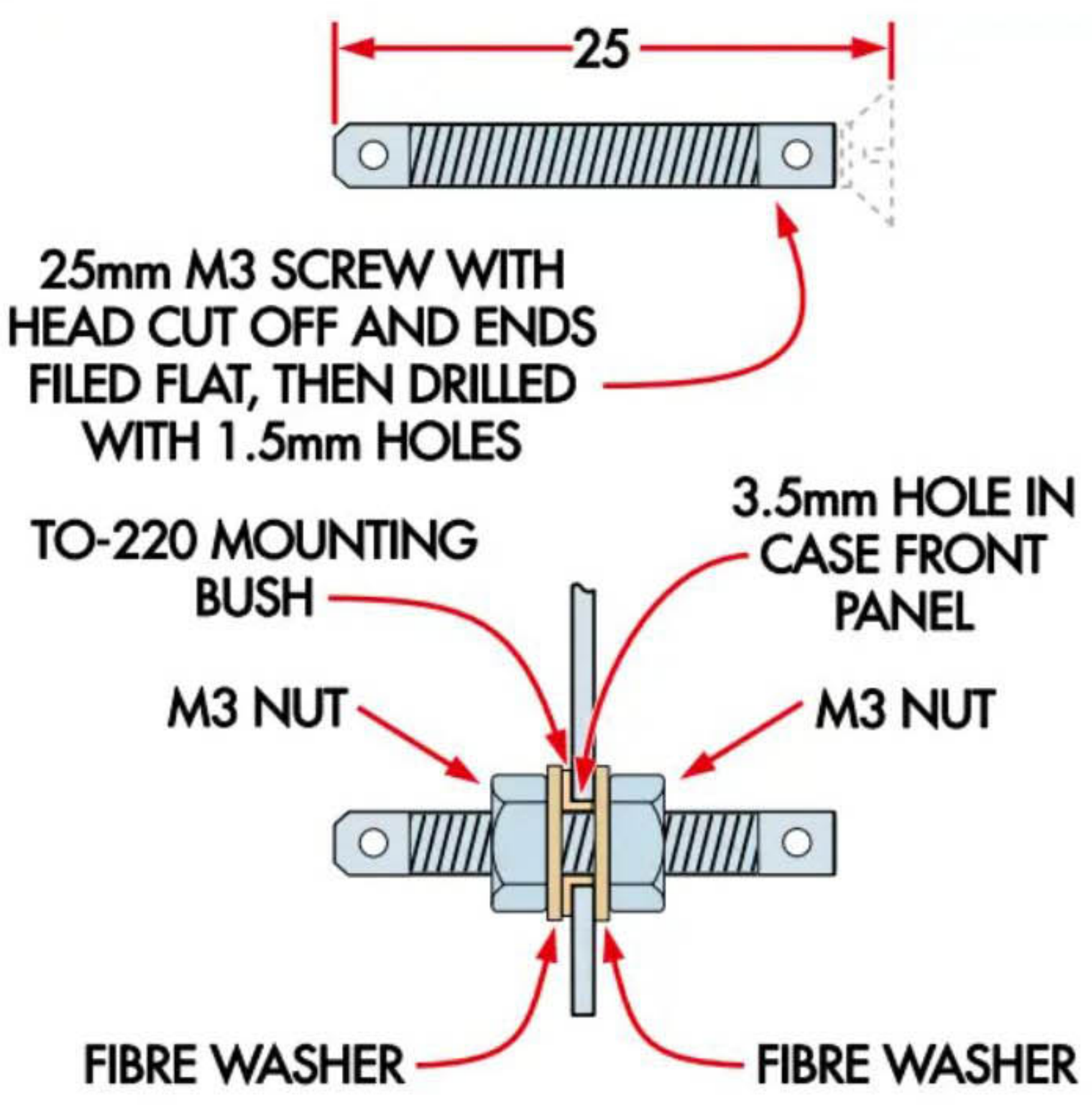
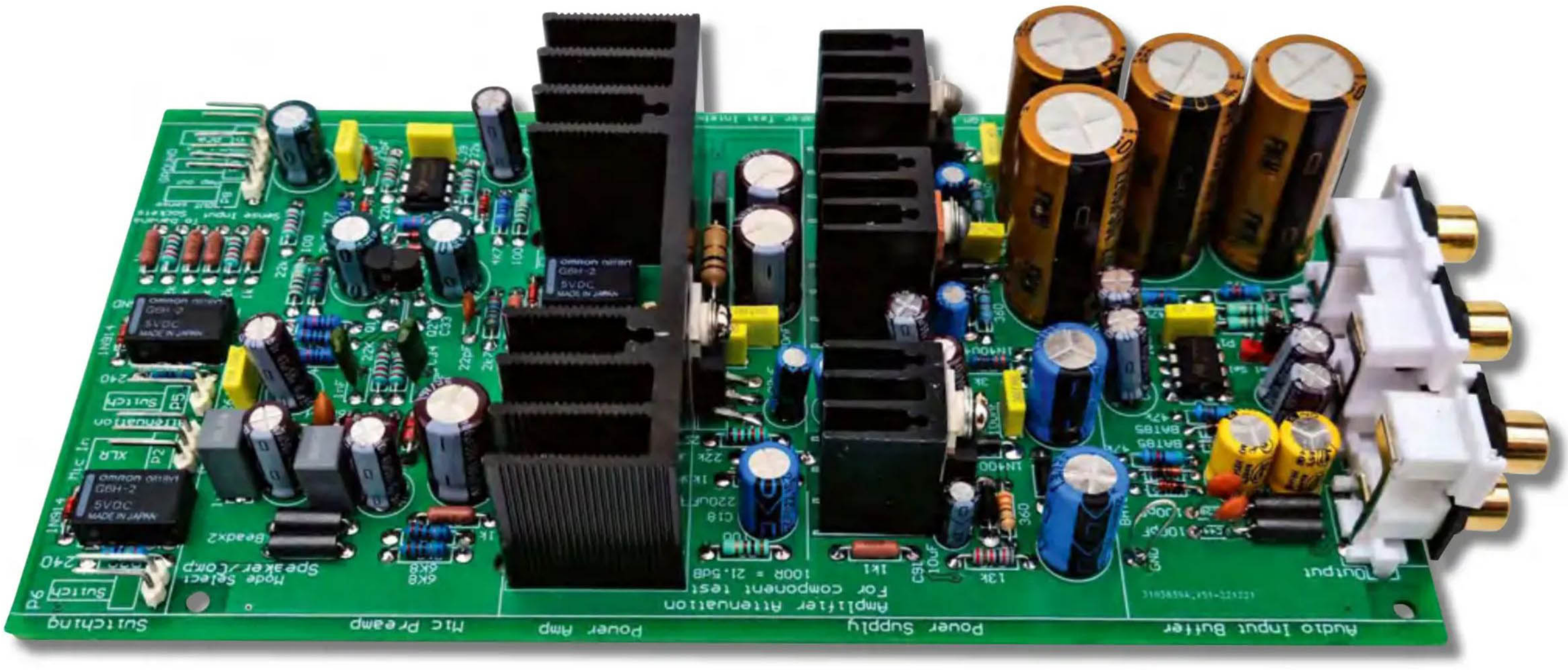

25
25mm M3 SCREW WITH HEAD CUT OFF AND ENDS FILED FLAT, THEN DRILLED WITH 1.5mm HOLES
TO-220 MOUNTING BUSH
3.5mm HOLE IN CASE FRONT PANEL
M3 NUT
M3 NUT
FIBRE WASHER
FIBRE WASHER

Fig.9: filing and drilling an M3 stud makes a convenient place to attach a test probe. However, you could devise your own scheme if you prefer; a loop of tinned copper wire would be sufficient.



The assembled PCB, ready to be wired up to the front panel via eight right-angle polarised headers. That makes plugging and unplugging easier when it is mounted in the instrument case.

With the case panels prepared, mount the front panel hardware. We used dual binding posts for the speaker connections, although you could save a little money by using captive-head binding posts. Whatever you choose, make sure they can act as both binding posts and banana sockets, as that is really handy in use.

After mounting the binding posts, follow with the three switches, then the XLR microphone socket. Watch your selection, as some XLR connectors are pretty deep and the mounting hole locations vary.

The last 'fiddly bit' is the microphone monitor output. We had very little space and wanted a test output for hooking an oscilloscope probe, similar to the calibration post on many oscilloscopes. We made ours from a 25mm M3 screw by cutting the head off with a hacksaw, filing each end flat, then drilling a 1.5mm hole through the flat parts using a PCB drill. That worked a treat, as shown.

Fig.9 shows the details. We soldered to this using plenty of flux. It is used for measuring the time alignment of speaker drivers.

Wiring it up

Cabling for the *Loudspeaker Test Jig* is made easy by using plugs on the end of the leads connected to the front panel, as shown in Fig.8. You need to make up the following flying leads, all using wires stripped from ribbon cable or light-duty figure-8, except the ground lead:

- **Four 150mm-long leads with two wires for:**
  - The Mic output monitor post (CON3)
  - The Output Attenuation switch (CON5)
  - The Mode switch (CON6)
  - The sense wires for the Amp Output and DUT (CON8)
- **One lead from medium-duty hookup wire for the ground connection (CON9).**

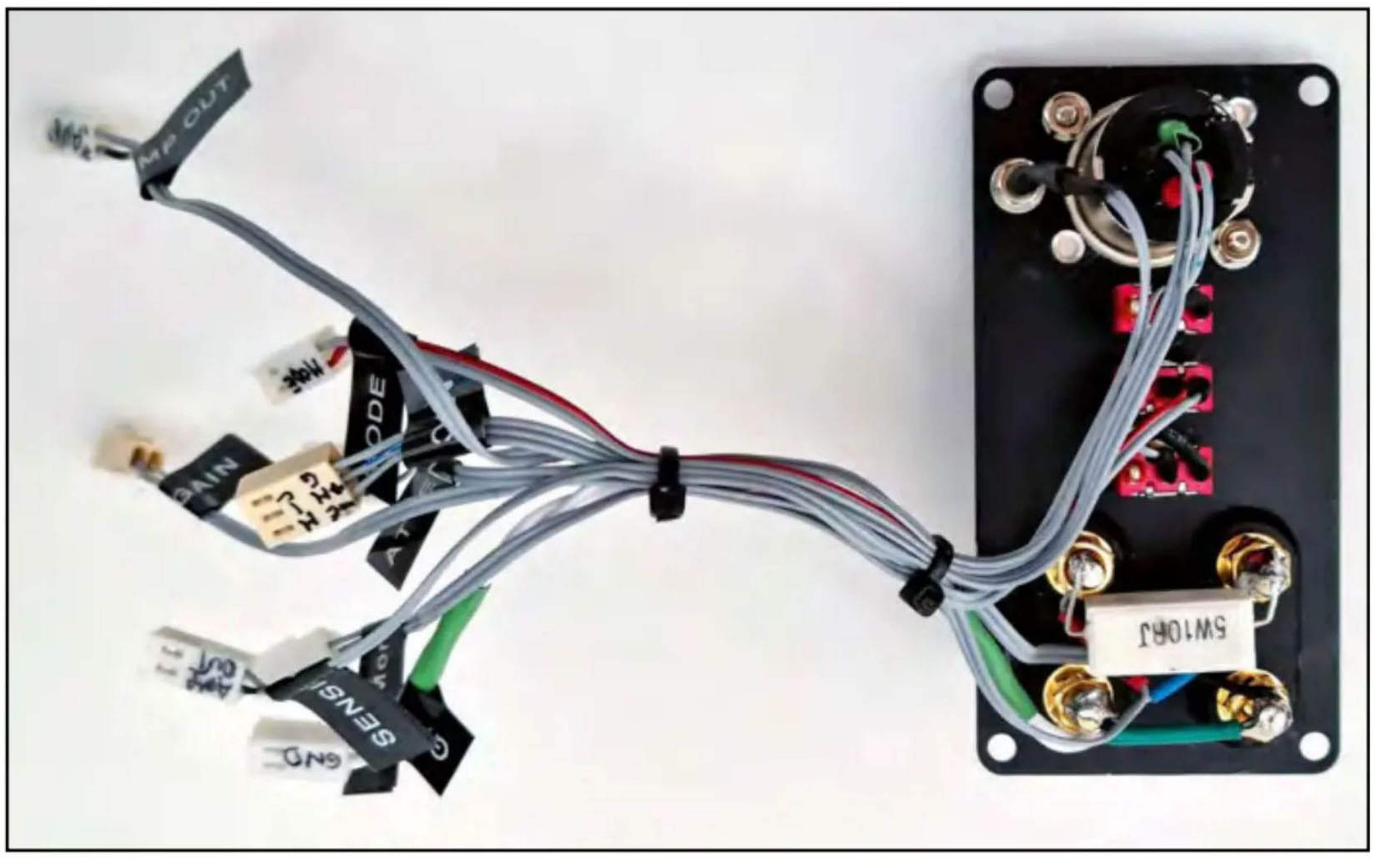


Photo 3: label the plugs and wire so that you don't get them mixed up when plugging them into the PCB headers. This photo also shows more clearly how the reference resistor is connected.

- **Two 200mm-long leads with two wires for:**
  - The amplifier output (CON4). Ideally, use two lengths of light-duty hookup wire.
  - The Mic Gain switch (CON7)
- **One 150mm-long lead with three wires for the Microphone input (CON2).**

Label these at the plug end so you will know what header they plug onto later. Also make sure you mark pin 1 on each lead; we used pieces of leftover heatshrink to mark pin 1. You could use a marker pen, but be aware that the marking could become less distinct with time and handling.

Wire up the board to the front panel connectors and controls, as shown in Fig.8. The best way to do this is:

- Solder the CON9 ground wires to the black pins on the banana sockets/binding posts. Jumper across them at the banana socket to 'double up' the ground wiring.
- Measure your 10W reference resistor with the best precision you can. Mark the reading on the resistor, so you don't forget the resistance. Securely bend the leads around the red posts of the 'Amp' and 'DUT' headers and solder them.
- Solder pin 1 of CON4 to the red terminal of the AMP banana socket. Pin 2 goes to ground.
- Solder pin 1 of CON8 to the red terminal of the DUT banana socket and pin 2 to the red terminal of the AMP banana socket.
- Solder the CON5 wires across the top two pins of the Atten switch on the front panel.
- Solder the CON6 wires across the top two pins of the Mode switch on the front panel.
- Solder the CON7 wires across the top two pins of the Mic Gain switch on the front panel.

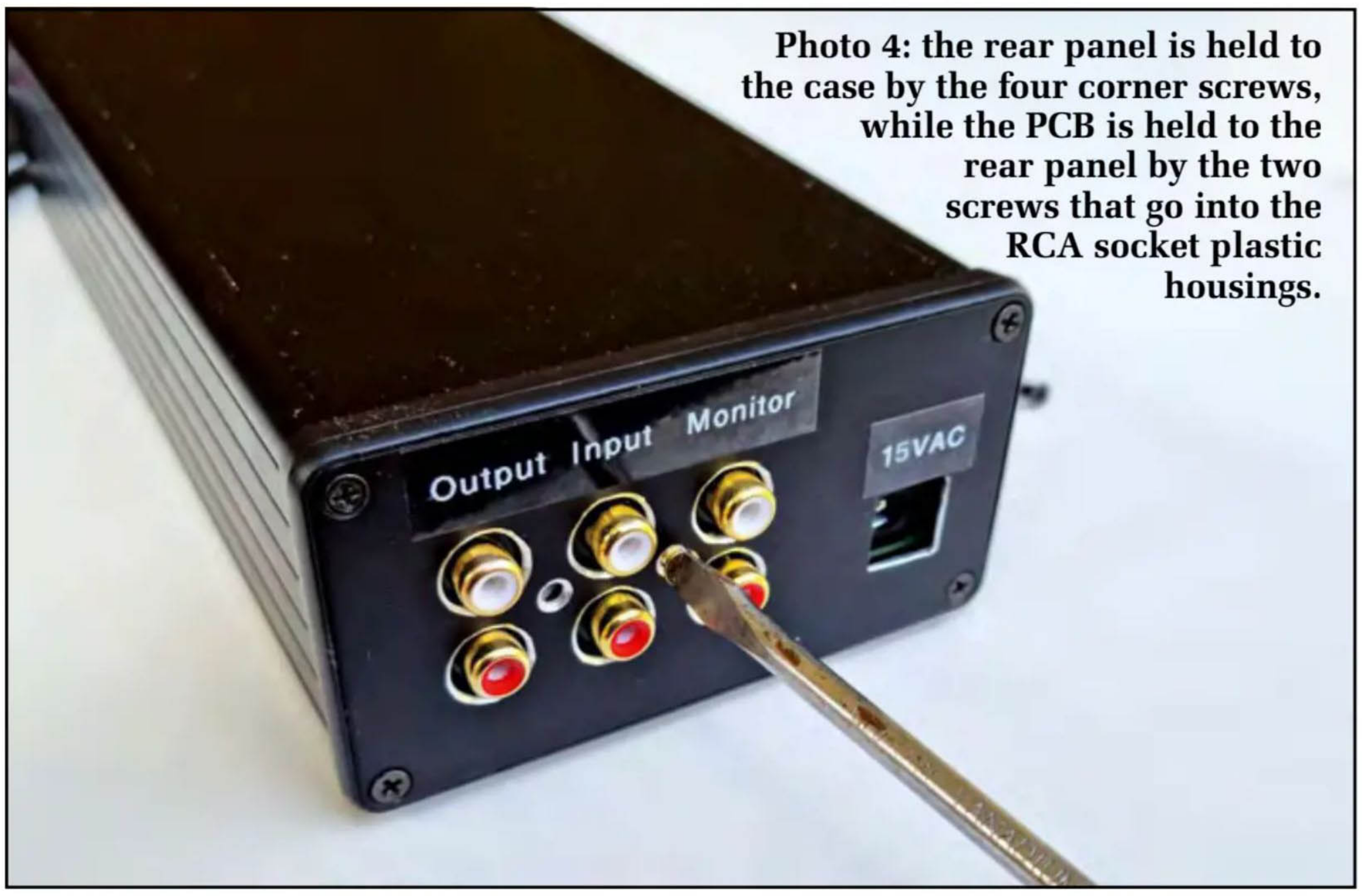


Photo 4: the rear panel is held to the case by the four corner screws, while the PCB is held to the rear panel by the two screws that go into the RCA socket plastic housings.

- Solder pin 1 of CON3 to the Mic Monitor post. Fold the ground wire back and insulate it.
- Solder pin 1 of CON2 to the ground pin of your XLR, pin 2 to hot (+) and pin 3 to cold (–).

These should all now plug in neatly to the PCB. Use a couple of tie wraps/cable ties to secure the wiring after checking that it all works. You are now ready to test it properly!

Once wired up, the front panel will look something like Photos 2 and 3.

Assembly to the rear panel just involves sliding the board into the case and using two 4G screws to secure the RCA connectors to the rear panel, as shown in Photo 4.

Operational testing

It's best to plug the front panel into the PCB before inserting the PCB into the case for testing, as you can't probe the test points on the PCB once it is in the case. When you've verified it's all working correctly, you can slide the PCB in and then attach the front panel.

Set the jumper for the input you expect to use for testing on JP1. Without this, the power amp will not get a signal, although most programs seem to drive both outputs with the test signal.

Apply a signal to the input (CON3a left and right) of 200mV RMS at about 1kHz. A buffered version of this signal should appear at CON3b. Toggle each switch and check that you hear the relays click. If not, check that you have used the correct relays and that the diodes are the right way around.

Set the 'Speaker/Comp' switch to Speaker. Monitor the Amp Out at pin 1 of CON4 and check that you see an amplified version of the input signal at about 2V RMS. Switch the 'Speaker/Comp' switch at CON6 and check that the output is attenuated in the 'Comp' position. This should be close to the amplitude of your test signal (about 200mV RMS).

Next, ensure you have the phantom power enabled by putting a shorting block on LK1 and check that you have 48V ±3V on the hot and cold pins of CON2. Plug in your test microphone and check for a signal on pin 1 of CON3 and your Mic test point on the front panel. If you have trouble, check that:

- There is about 10.3V across the 10kΩ resistors connected to the emitters of Q1 and Q2 (both above and to the left of Q1).
- There is about 3.7V across the 4.7kΩ resistors at the collectors of Q1 and Q2 (next to D7 and D8), and that these voltages are the same.
- Pin 1 of IC2 is close to 0V.

If any of these are wildly off, verify the component values and orientations in these areas; check for short circuits and that you have used the right transistors.

Testing, calibration and usage

With the unit now assembled and working, the next step will be to install the software, set it up and verify that it's working as expected. As the 'REW' software is not tied to this hardware, we have those instructions in a small separate article starting on page 40.

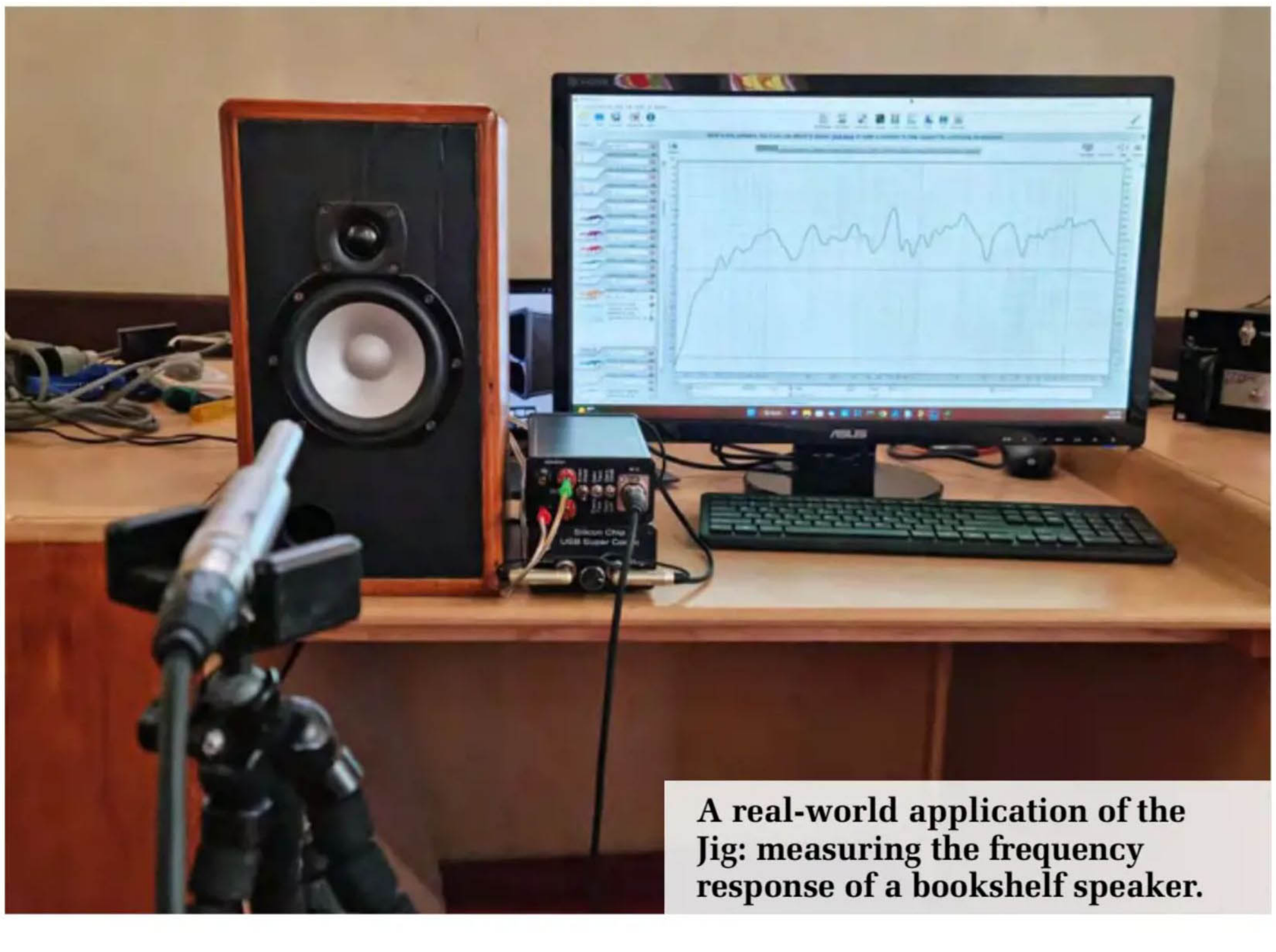
You will need a computer with a reasonably good sound card that has stereo analogue inputs and outputs to hook up to the *Loudspeaker Test Jig*. If your computer lacks those, consider building our very high-quality external *USB SuperCodec*, described in the September to November 2021 issues.

That unit is capable of simultaneous 192kHz, 24-bit recording and playback and has a rated THD figure of just 0.0001% (-120dB) and a THD+N figure of 0.0005% (-106dB) for playback and 0.00063% (-105dB) for recording. You don't need a sound card with such high quality for speaker testing, but it certainly doesn't hurt!

Whatever sound card you use, go into your operating system's settings and ensure it is the active device for recording and playback. In recent versions of Windows, you can do that by right-clicking the speaker icon in the screen's lower right-hand corner and selecting 'Open Sound settings'.

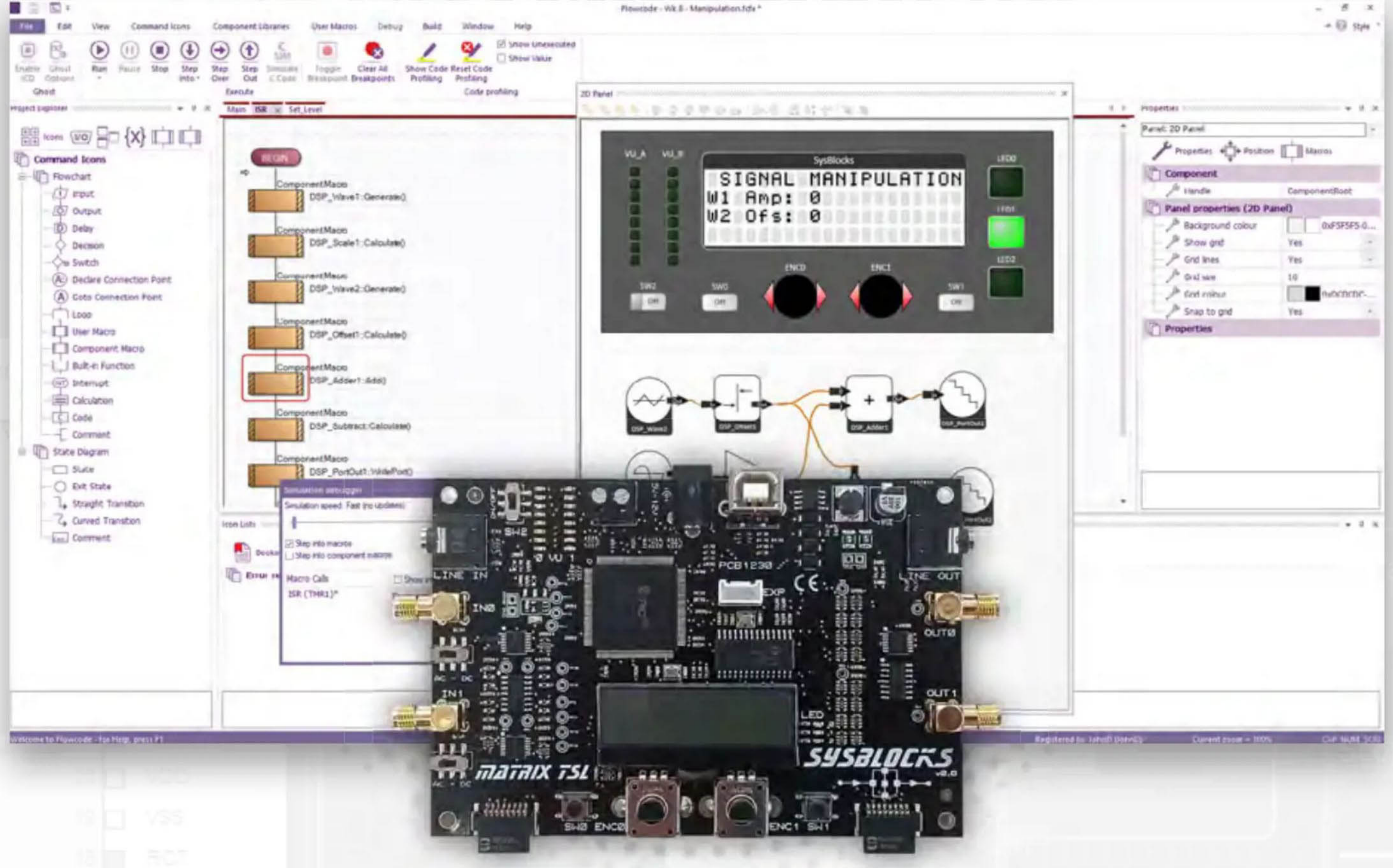
If your sound card's sockets are 3.5mm jack sockets, you can use 3.5mm jack plug to twin RCA plug cables to connect them to the Input and Output sockets on the Loudspeaker Testing Jig. If the sound card has RCA sockets, like the SuperCodec, use twin RCA to RCA leads instead. Then, connect the Monitor outputs to your amplifier inputs with a twin RCA to RCA lead.

When ready, turn to page 40 for the final testing procedure.



A real-world application of the Jig: measuring the frequency response of a bookshelf speaker.

Sysblocks



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SETTING UP AND USING ROOM EQ WIZARD

This accompanying article for the Speaker Test Jig explains how to set up and use the freely-available Room EQ Wizard (REW) or Speaker Workshop software to help you design and tweak loudspeakers.

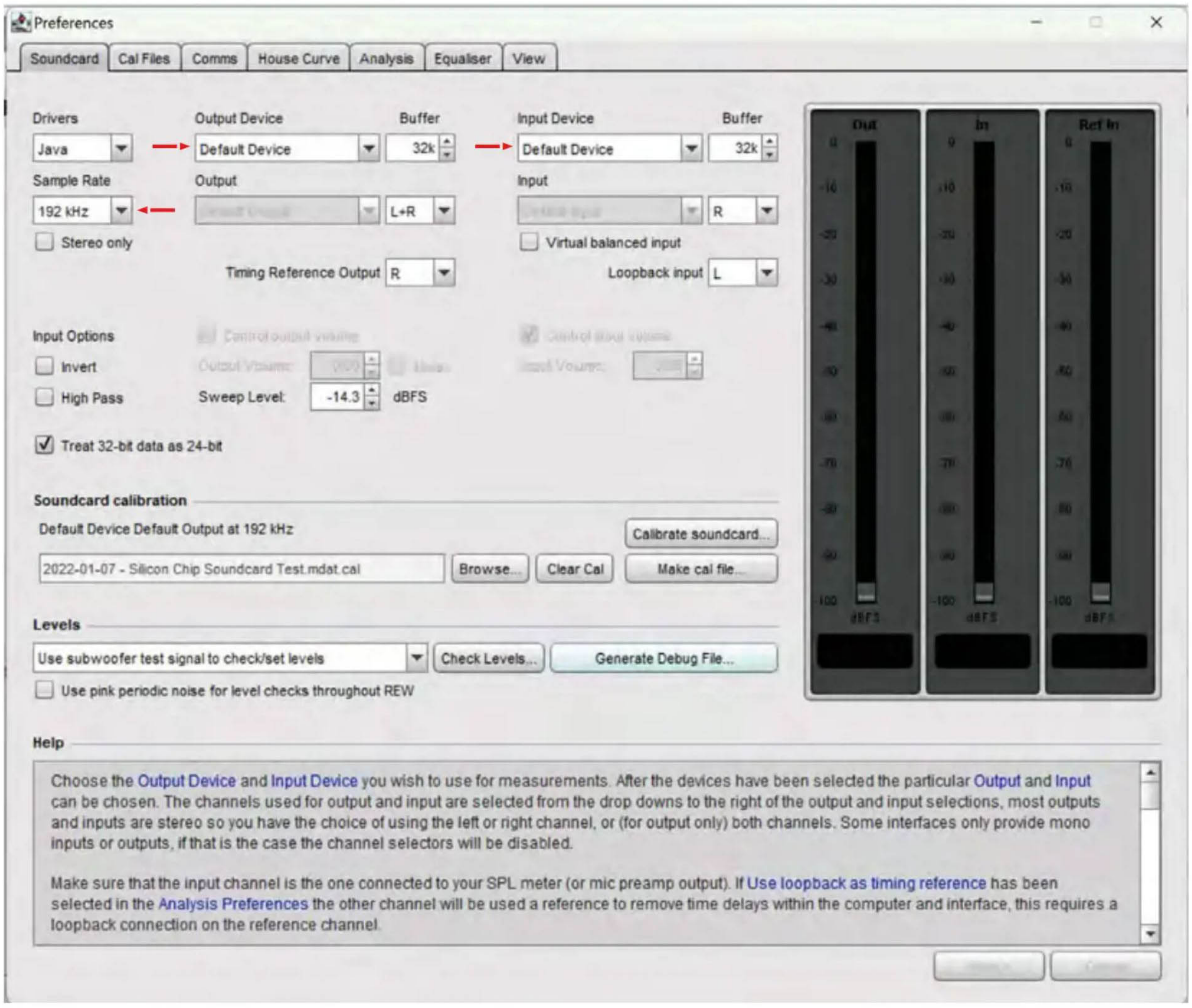
By Phil Prosser

First off, you don't need the *Loudspeaker Test Jig* described in this issue to use Room EQ Wizard or Speaker Workshop to design and test loudspeakers and drivers, but it makes it a lot easier.

This article will describe setting up and using REW (and later, Speaker Workshop) assuming you have built the *Loudspeaker Test Jig*. If you haven't, you can still follow these procedures; you just need to rig up a microphone preamp, power amplifier, test resistor and some other bits and pieces to perform similar functions.

Essentially, what you need (and the *Jig* provides) for measuring driver impedance is to have your computer's sound card feeding a power amplifier that drives the device under test (DUT) via a well-characterised 10Ω or similar power resistor. Both ends of that resistor then connect to the two sound card inputs.

For driver and speaker frequency response plots, you instead need a calibrated microphone and microphone preamp combination that gives a flat response feeding into one of your sound card's inputs while the output(s) drive the DUT via a small power amplifier. The *Jig* also does that if you have a calibrated microphone (we'll describe an inexpensive one in an upcoming issue).



Drivers: Java

Output Device: Default Device — Buffer: 32k

Input Device: Default Device — Buffer: 32k

Sample Rate: 192 kHz

Output: L+R

Input: R

☐ Stereo only

☐ Virtual balanced input

Timing Reference Output: R

Loopback input: L

Input Options

☐ Invert

☐ High Pass

Sweep Level: -14.3 dBFS

☑ Treat 32-bit data as 24-bit

Soundcard calibration

Default Device Default Output at 192 kHz

2022-01-07 - Silicon Chip Soundcard Test.mdat.cal

Levels

Use subwoofer test signal to check/set levels

☐ Use pink periodic noise for level checks throughout REW

Help

Choose the Output Device and Input Device you wish to use for measurements. After the devices have been selected the particular Output and Input can be chosen. The channels used for output and input are selected from the drop downs to the right of the output and input selections, most outputs and inputs are stereo so you have the choice of using the left or right channel, or (for output only) both channels. Some interfaces only provide mono inputs or outputs, if that is the case the channel selectors will be disabled.

Make sure that the input channel is the one connected to your SPL meter (or mic preamp output). If Use loopback as timing reference has been selected in the Analysis Preferences the other channel will be used a reference to remove time delays within the computer and interface, this requires a loopback connection on the reference channel.

Screen 1: the REW Preferences dialog. Check that the input and output devices and sampling rate settings are set correctly.

Final testing and setting up REW

We assume you have your computer set up and your sound card properly installed. Importantly, make sure you have the sample rate set and no effects turned on. Also check that you do not have 'monitor recordings' set.

The critical steps to getting the *Loudspeaker Test Jig* operational with the REW software are provided here. There are many resources on the internet for this program, and its full details are well beyond the scope of this article. Still, let's get it up and running.

After installing and launching REW, to set it up, open the preferences pulldown and then the preferences tab – see Screen 1. Select your input and output here; usually, you would use the default sound input and output devices.

Calibrating your sound card

1. Set the *Loudspeaker Test Jig* to 'component test' and make sure there is nothing connected to the Speaker and DUT connectors.
2. Make sure the *Loudspeaker Test Jig* attenuator is switched out.
3. In REW, open the preferences pulldown and open the preferences tab.
4. Click on 'Calibrate soundcard'. Note that by using the 'Component' test mode, the 10Ω reference resistor acts as the loopback mentioned in the text box that will pop up.
5. Click Next, and a text box will appear providing instructions. Follow them.

6. Click Next and check that you have levels that are about right. You should find that with about 200mV RMS output, you see a measured signal in the region of -10dB on the loopback test. Sound cards vary in sensitivity, so your voltages may vary somewhat from ours.
7. Then click Next until the measurement sweep is made. You will get a graph similar to that in Screen 2.
8. On the tab for the measurement you just made, add any notes you need. Then click the disk symbol on the measurement and save this file somewhere sensible.
9. Now press Alt+Tab to switch back to the preferences screen and click on 'Make Cal File', which is below the 'Calibrate Sound Card' button.
10. Navigate to where you saved the previous measurement. Select 'all files' from the pulldown 'files of type' and then select your calibration measurement. Click 'Save'.
11. Your sound card is now calibrated.

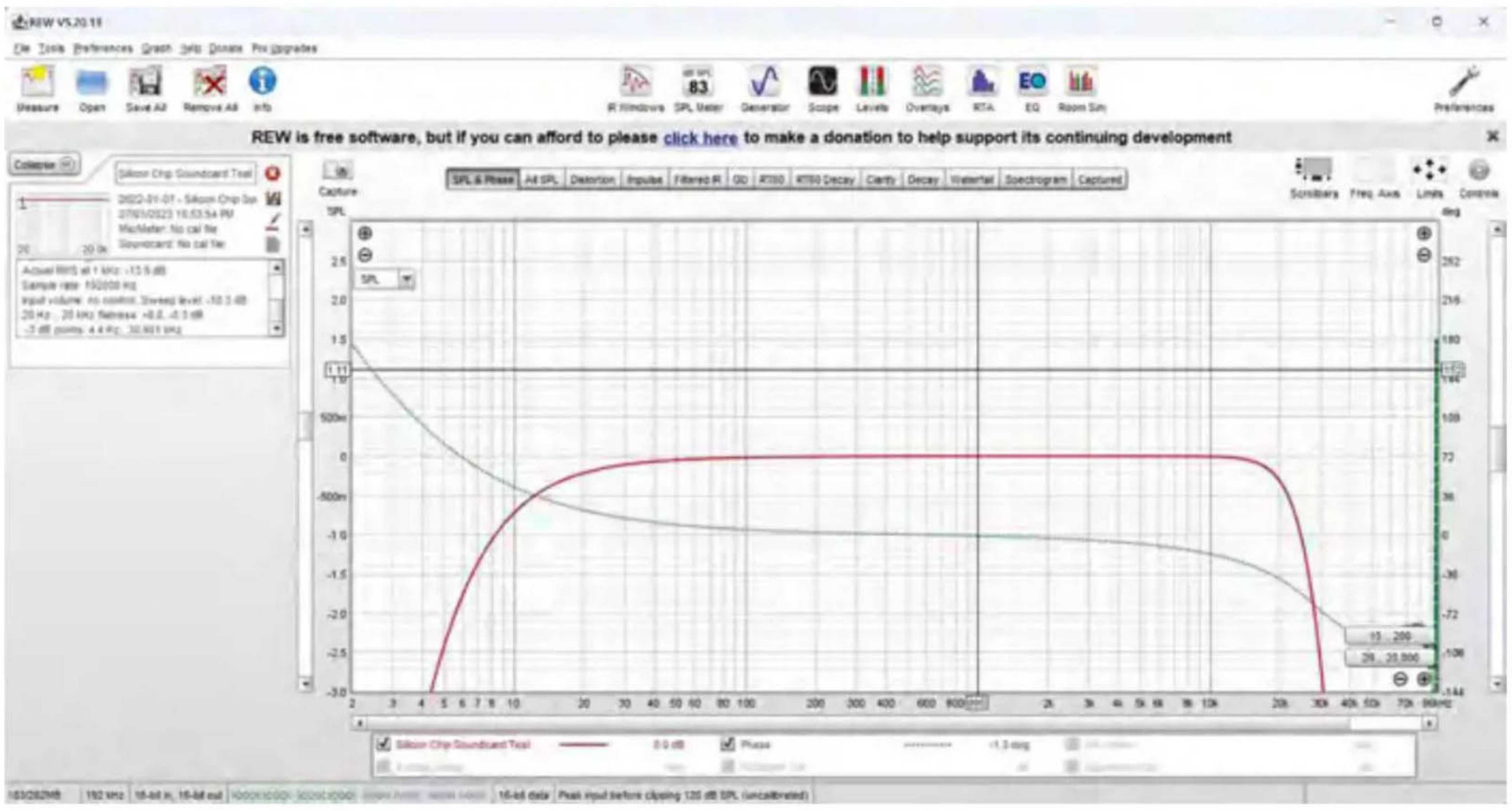
Calibrating the Test Jig

1. Set your *Loudspeaker Test Jig* to 'component' test and ensure there is nothing connected to the Speaker and DUT connectors and that the Attenuator is out.
2. You only need to do this on the first measurement you make. Click 'Measure' in the top left corner of the main REW screen (Screen 3). If you have not calibrated the SPL, you will get a message box; you can ignore it for now.
3. Now enter your sense resistor value in the Rsense box at the right of this window.
4. Click on 'Open Circuit Cal' and follow the instructions. Save the file along with your others. Do the same for 'Short Circuit Cal' and use a known resistor value for 'Reference Cal'.
5. You can now measure an impedance. A window similar to that shown in Screen 4 will pop up. Screen 5 shows the measured impedance of a subwoofer.

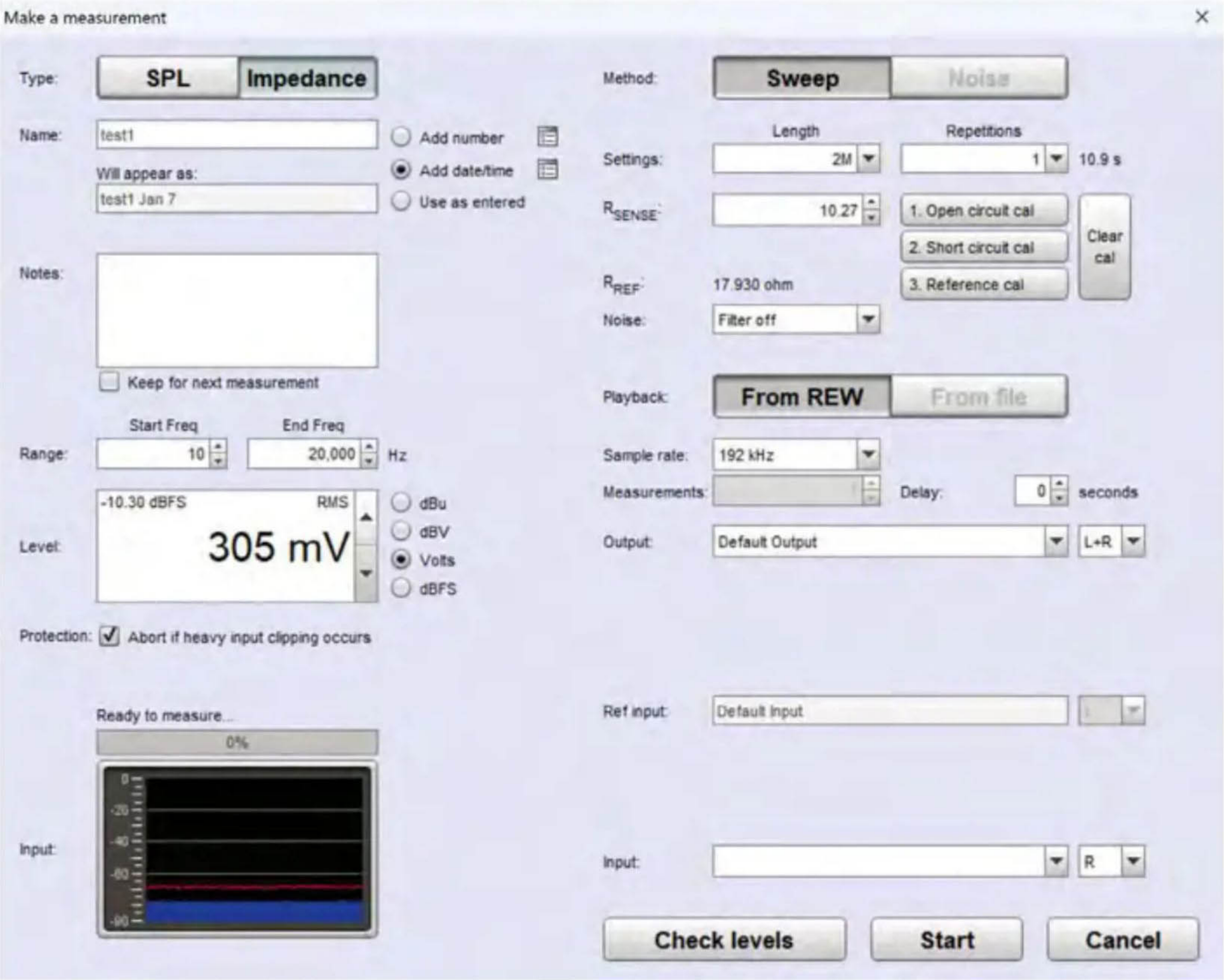
Using it

To measure an impedance

1. Set your *Loudspeaker Test Jig* to 'component' test and make sure there is nothing connected to the Speaker and DUT connectors and that the Attenuator is out.
2. Click 'Measure' in the top left corner of the main REW screen.
3. Click 'Impedance' in the top left of the screen, as shown in Screen 3.
4. Click Start once you have connected your unknown impedance across the DUT terminals.

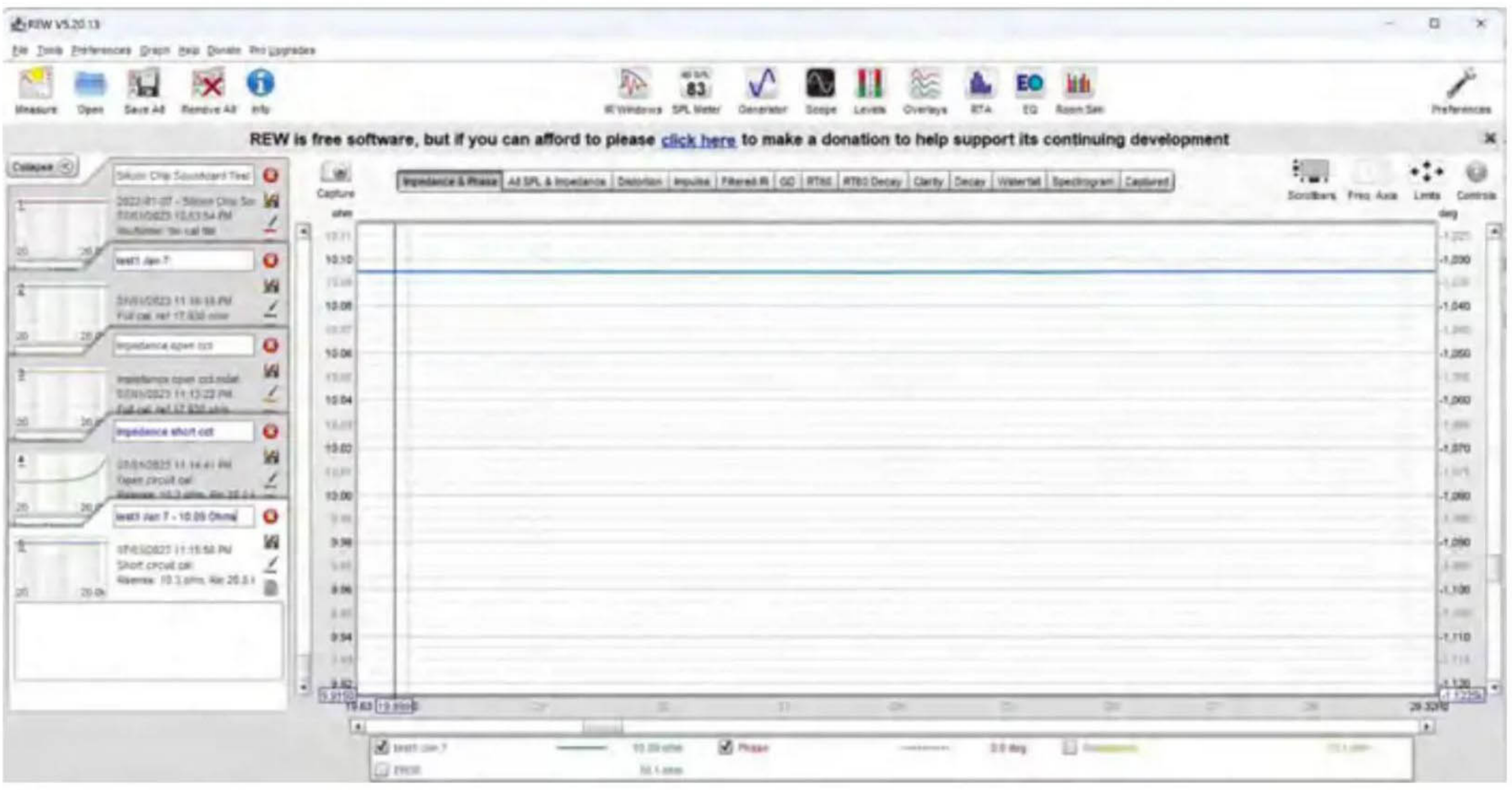

REW V5.20.13
Measure
Open
Save All
Remove All
Info
Preferences
REW is free software, but if you can afford to please click here to make a donation to help support its continuing development
SPL & Phase
Silicon Chip Soundcard Test
Phase

Screen 2: this shows the frequency response REW has calculated for the measurement system, including the computer sound card.


Make a measurement
SPL
Impedance
Sweep
Noise
1. Open circuit cal
2. Short circuit cal
3. Reference cal
Clear cal
From REW
From file
Check levels
Start
Cancel

Type: Impedance
Name: test1
○ Add number
● Add date/time
○ Use as entered
Will appear as: test1 Jan 7
Notes:
☐ Keep for next measurement
Range: Start Freq 10 End Freq 20,000 Hz
Level: -10.30 dBFS RMS 305 mV
○ dBu
○ dBV
● Volts
○ dBFS
Protection: ☑ Abort if heavy input clipping occurs
Ready to measure...
0%
Input:
Method: Sweep
Settings: Length 2M Repetitions 1 10.9 s
R_{SENSE}: 10.27
R_{REF}: 17.930 ohm
Noise: Filter off
Playback: From REW
Sample rate: 192 kHz
Measurements:
Delay: 0 seconds
Output: Default Output L+R
Ref input: Default Input
Input: R

Screen 3: you make impedance and frequency response measurements using this screen in the REW software.

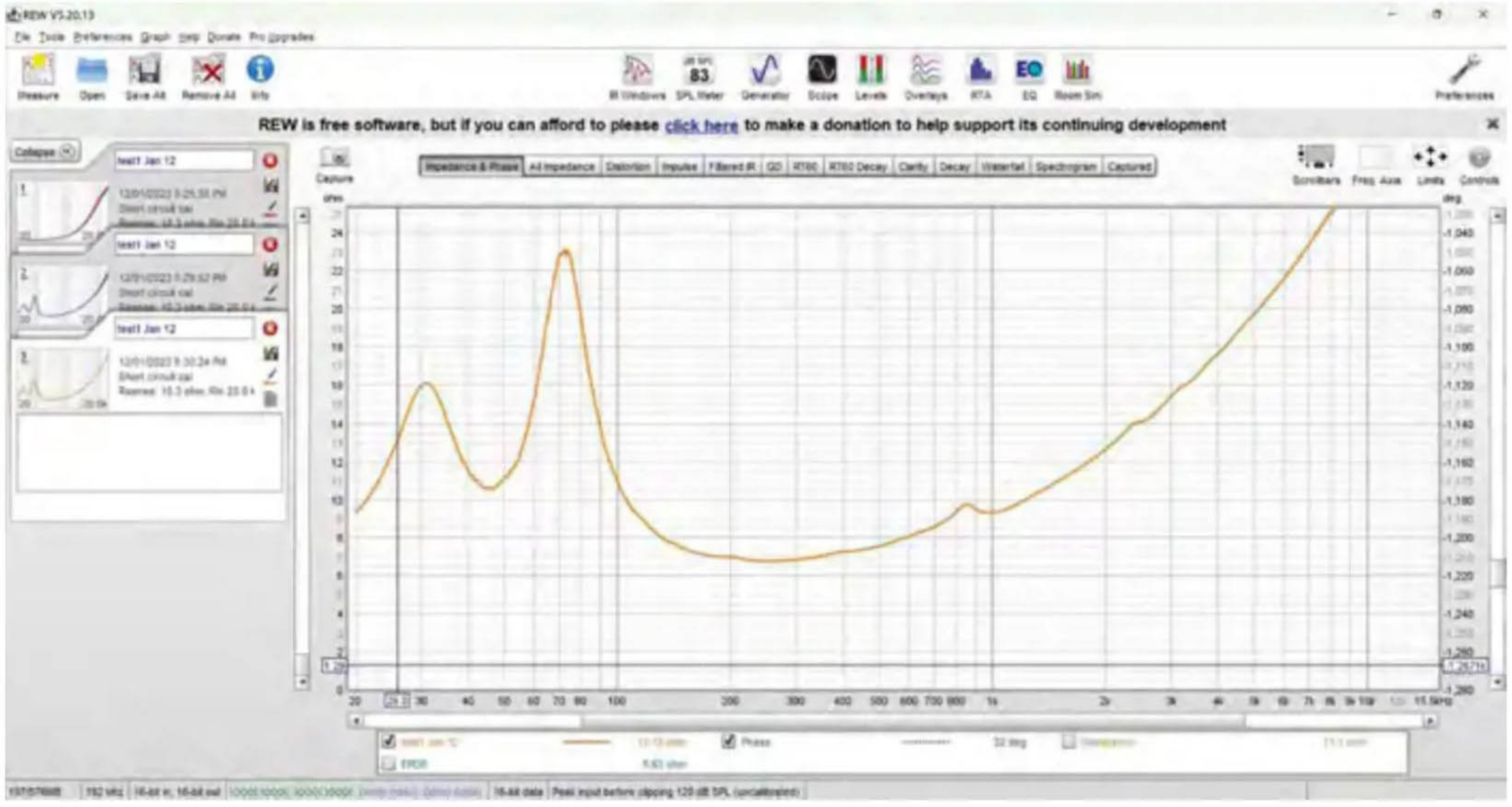

REW V5.20.13
Measure
Open
Save All
Remove All
Info
Preferences
REW is free software, but if you can afford to please click here to make a donation to help support its continuing development
Impedance & Phase

Screen 4: calibration with our 10Ω test resistor is complete, and the result almost exactly matches what our Low Ohms Meter reads.

To measure speaker frequency response

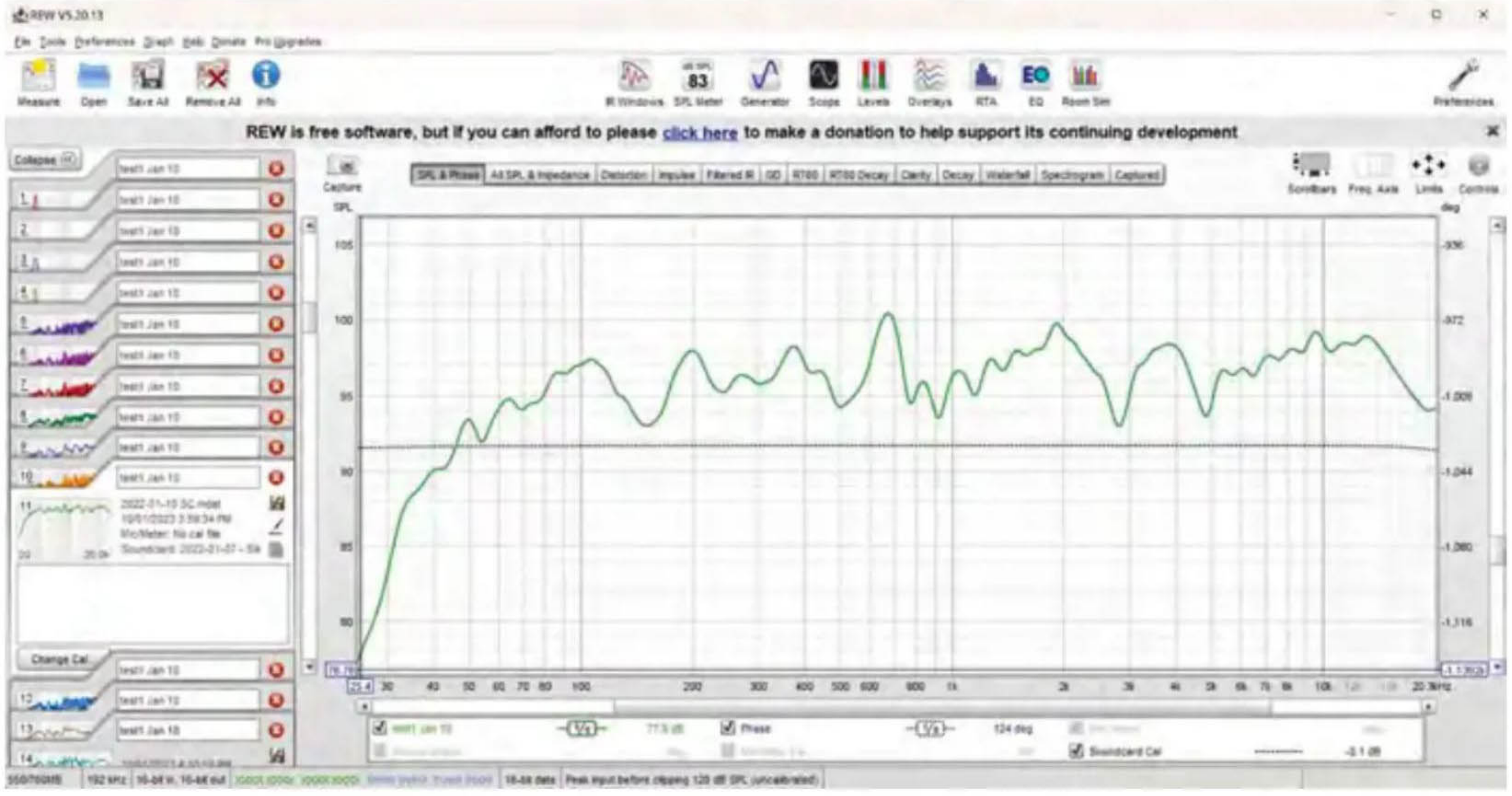
1. If you are testing a tweeter, put a high-value non-polarised capacitor in series to protect it from low frequencies, and consider running the sweep from, say, 500Hz up.
2. Set your *Loudspeaker Test Jig* to 'speaker' test.

3. Connect your speaker across the Speaker terminals.
4. Plug your microphone in and set the microphone gain as required.
5. Set the attenuator on or off depending on the level you intend to test at.
6. Click Measurement again, and this time select 'SPL'.


REW V5.20.13
File Tools Preferences Graph Help Donate Pro Upgrades
Measure Open Save All Remove All Info
IR Windows SPL Meter Generator Scope Levels Overlays RTA EQ Room Sim
Preferences
Impedance & Phase
Capture
ohm
deg

REW is free software, but if you can afford to please click here to make a donation to help support its continuing development

Screen 5: a measurement of the impedance of a subwoofer taken using REW and our Test Jig. It gives a nice smooth plot that shows resonance peaks at about 31Hz and 72Hz (driver/box) plus 850Hz and 2.5kHz (cone breakup).


REW V5.20.13
File Tools Preferences Graph Help Donate Pro Upgrades
Measure Open Save All Remove All Info
IR Windows SPL Meter Generator Scope Levels Overlays RTA EQ Room Sim
Preferences
SPL & Phase
Capture
SPL
Change Cal

REW is free software, but if you can afford to please click here to make a donation to help support its continuing development

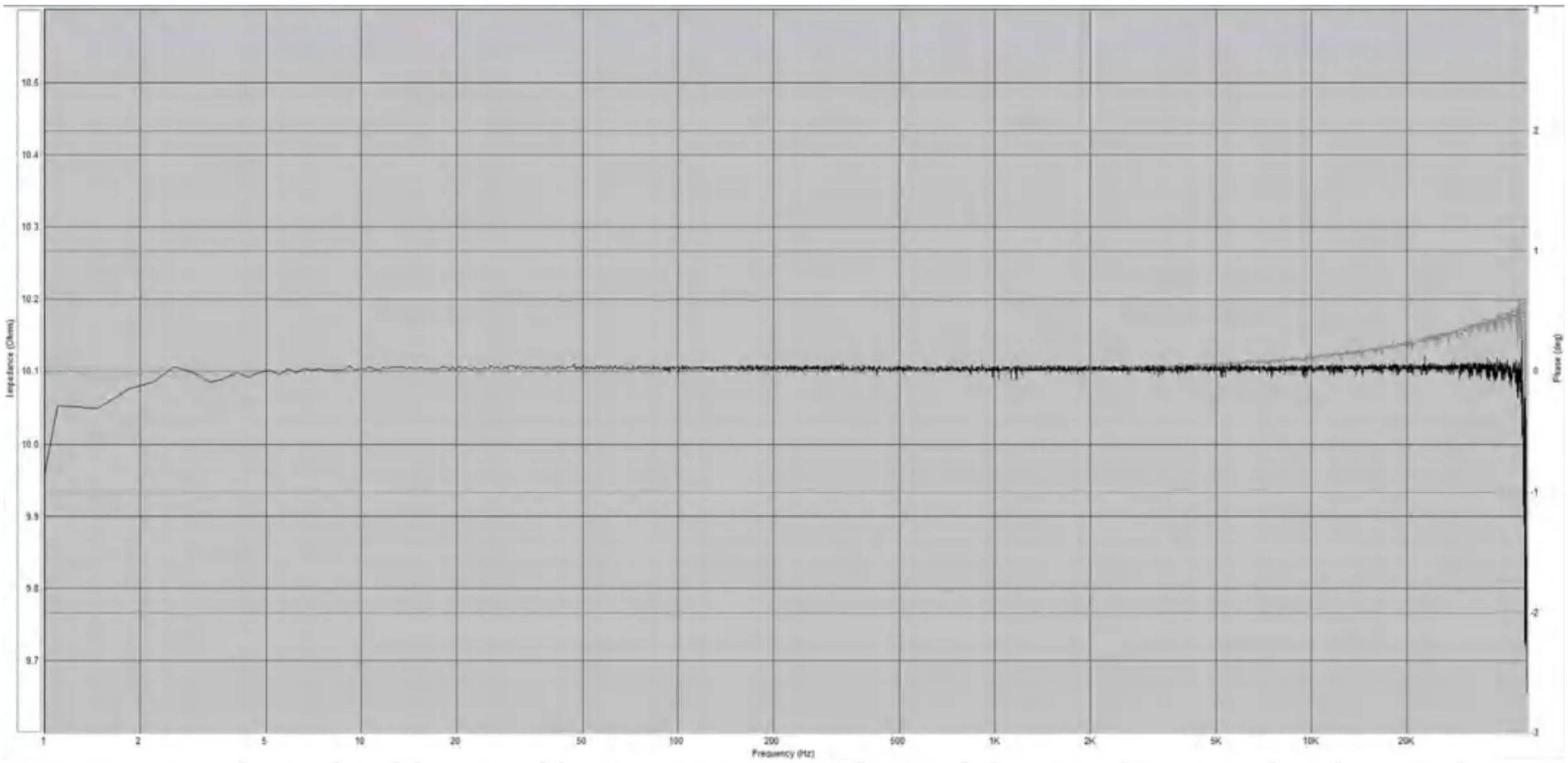
Screen 6: a frequency response plot of a wide-range driver made using REW. This sort of information is invaluable in speaker design and tweaking.

7. The system will run a sweep and you will hear the chirp.
8. Check that the levels are reasonable. If necessary, adjust the sound card output level, the microphone gain switch and the output Attenuator for the *Loudspeaker Test Jig*. You will find that once you are set up for testing, these don't change often.
9. Watch the levels; if the outputs or inputs clip, you will get odd results. If this happens, investigate the cause and correct it.
10. You will see the result pop up in a window similar to that in Screen 6, a very rough plot of a speaker done on our workbench.
11. You can change the smoothing setting, show a waterfall plot, show distortion and a range of other plots from this measurement, which is pretty impressive.

Tips

- **The room will play havoc with far-field measurements. If you do this in a room, you will never get a 20Hz to 20kHz plot without all sorts of peaks and dips. Just accept this.**
- **You will need to apply smoothing to get a plot anything like what you see in Hi-Fi magazines, as that is what they do.**
- Testing outside is good; the ground is always there, though. This will generate 'ground bounce', which is perfectly natural, and you need to work around this unless you point your speaker up and hang your microphone from a ladder. Yes, we have done this!

From here, we recommend that you explore some of the excellent



Screen 8: an impedance plot of the 10Ω calibration resistor in Speaker Workshop. It's a bit noisier than the equivalent REW plot, but it demonstrates that the measurement system is accurate from about 5Hz to over 20kHz. Note that this plot was made as part of the verification process of the Loudspeaker Test Jig.

resources on the Internet for these programs. REW is more active, but Speaker Workshop has a strong following. The DIY audio community has several quite active groups. 'DIY Audio' is a good place to start finding like-minded people.

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How to get Speaker Workshop up and running

If you want to try out Speaker Workshop, read relevant parts of the 'unofficial manual' on the download page at: **www.claudionegro.com**

Ignore the 'failed to update system registry' warning on startup. You must set up a project:

1. Create a new file by clicking on 'File' then 'New'.
2. This program works by adding resources to the 'system'. Resources might be an enclosure, driver or network.
3. You need to add a driver at minimum. To do this, open the 'Resource' menu and select 'New' then 'Driver'. You need to select this to make measurements – see Screen 7.

To calibrate the system:

1. From the 'Options' menu, select 'Calibrate'.
2. Make sure there are no leads connected to the Amp and DUT jumpers on the Test Jig.
3. Switch the Jig to 'Comp' and switch the measurement attenuator out. In this position, both sound card channels measure the amplified output.
4. Click 'Test' on the channel difference box. Follow the instructions to run the calibration, finishing with 'OK' to accept it.

After calibration, look at the bottom left of the screen. This shows the digital values read in the calibration. The maximum must always be less than ±32768 and ideally in the 10,000-20,000 region. Adjust your PC's output level and Jig attenuator setting until you get sensible readings. We generally find that an output level in the region of 40% works well.

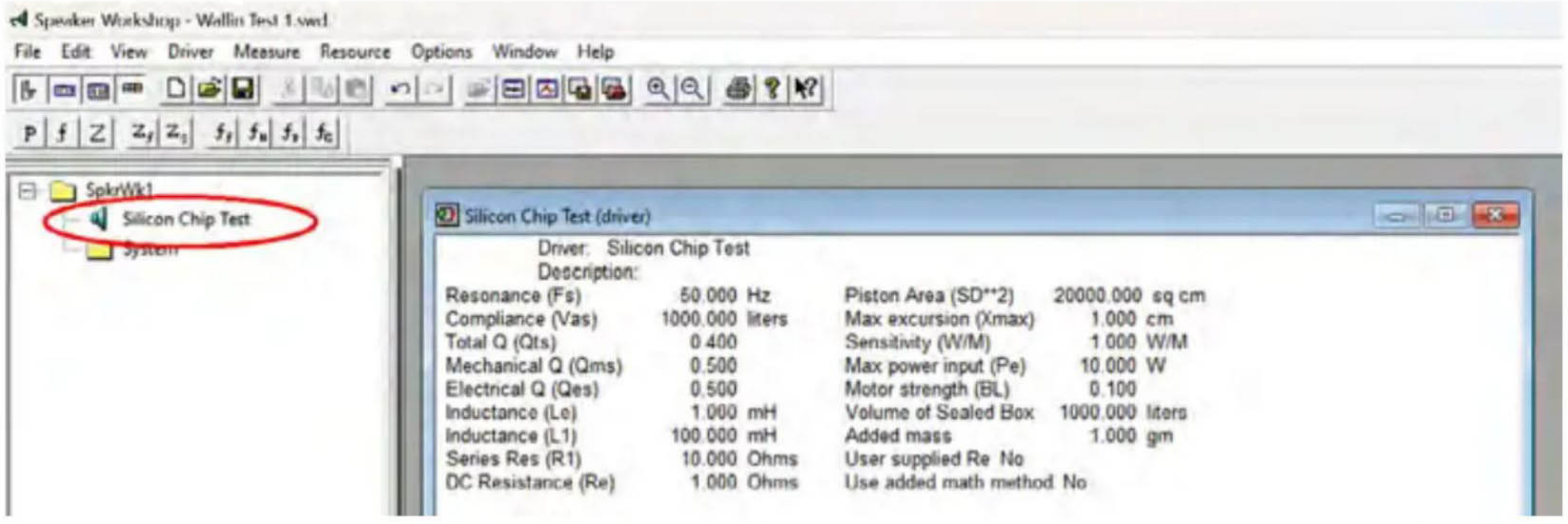
To set the Reference, open the 'Options' menu, then the 'Preferences' tab. Click on the 'Impedance' tab and type the exact resistance of your reference resistor in the Impedance Jig definition box.

To make an impedance test:

1. Connect your DUT between the DUT and ground terminals.
2. Select the driver we created earlier. It will become highlighted in blue.
3. Open the 'Measure' menu and click on 'Impedance'.
4. Once the measurement is complete, check that the values at the lower left of the screen are reasonable. You should see a window pop up with the measurement, as shown in Screen 8. Our Low Ohms Meter measured this resistor as 10.09Ω.
5. If the impedance plot is very fuzzy, check that you are not clipping the sound card or amplifier.

To make a speaker frequency response test:

1. Switch the Jig to SPKR.
2. Switch the attenuator next to the DUT connector in.
3. Connect a driver to the AMP output, not the DUT output.
4. Plug in your test microphone and place it close to your speaker.
5. Click on the driver icon you created and then select the 'Measure' pulldown, select the 'Frequency response' tab, then 'Nearfield'.
6. You should get a reasonably clean frequency response. It will have more noise than one from REW and may need smoothing. If the frequency response graph is very fuzzy, check that you are not clipping the sound card or amplifier.



```
        Driver:  Silicon Chip Test
        Description:
Resonance (Fs)           50.000  Hz       Piston Area (SD**2)    20000.000  sq cm
Compliance (Vas)       1000.000  liters   Max excursion (Xmax)       1.000  cm
Total Q (Qts)             0.400           Sensitivity (W/M)          1.000  W/M
Mechanical Q (Qms)        0.500           Max power input (Pe)      10.000  W
Electrical Q (Qes)        0.500           Motor strength (BL)        0.100
Inductance (Le)           1.000  mH       Volume of Sealed Box    1000.000  liters
Inductance (L1)         100.000  mH       Added mass                 1.000  gm
Series Res (R1)          10.000  Ohms     User supplied Re  No
DC Resistance (Re)        1.000  Ohms     Use added math method  No
```

Screen 7: to use Speaker Workshop with the Test Jig, you must create a 'driver' instance and set some critical parameters.

PoLabs
For more information or
software download please visit
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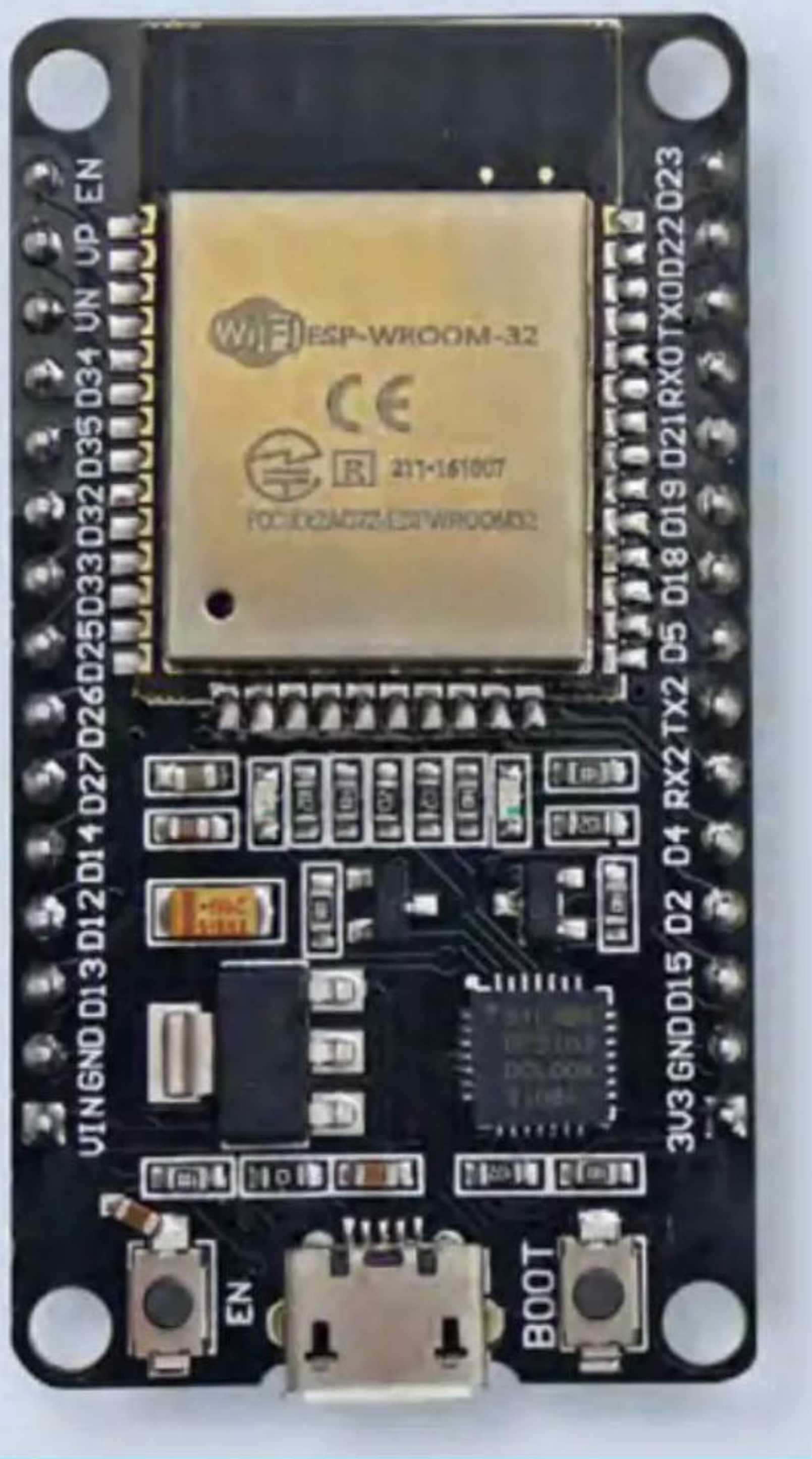
Teach-In 2024

Learn electronics with the ESP32

by Mike Tooley

Part 4 – Using LED displays



In the last month's part of our Teach-In series, we introduced the ESP32's ADC and DAC. We showed you how to read analogue voltages and interface analogue sensors. We also introduced the ESP32's Analogue Plotter as a means of visualising voltage changes over time. Plus, we explained the principle of pulse-width modulation (PWM) and how this is used to generate (pseudo) analogue output voltages and waveforms. *Coding Workshop* introduced the decimal, binary, octal and hexadecimal number systems. Our *Teach-in* project featured the design, construction and coding of a simple tester for 1.5V batteries.

The learning objectives for this fourth part of our series are to know how to:

- Configure and use matrix and seven-segment LED displays
- Interface a motion sensor.
- Generate and use random numbers.

About Teach-In

Our latest *Teach-In* series is about using the popular ESP32 module as a basis for learning electronics and coding. We will be making no assumptions about your coding ability or your previous experience of electronics. If you know one but not the other, you have come to the right place. On the other hand, if you happen to be a complete newbie there's no need to worry because the series will take a progressive hands-on approach. There will be plenty of time to build up your knowledge and plenty of opportunity to test things out along the way.

We've not included too much basic theory because this can be easily found elsewhere, including several of our previous *Teach-In* series, see:

https://bit.ly/pe-ti
https://bit.ly/pe-ti-bundle

Earch month, there'll be projects and challenges to help you check and develop your understanding of the topics covered.

Seven-segment LED displays

Seven-segment LED displays provide you with a simple, low-cost method of displaying numbers and a limited range of basic text characters. They comprise seven (or sometimes eight) individual LEDs arranged as shown in Fig.4.1. Note that the segments are lettered in sequence from the top, moving clockwise around the display and ending with the centre segment. Each of the segments, labelled 'a' to 'g', are individually addressable, which means that you can choose to illuminate one or all of them by applying a small current of typically 5 to 15mA to the segment required. In some displays an extra decimal point (referred to as 'd.p.' or 'DP') is also present.

Seven-segment displays are commonly available in various sizes and may be either common-cathode or common-anode types depending on which LED connections are linked together. Thus, for example, the common-cathode display shown in Fig.4.3(a) has nine connections, of which eight are used for the anodes of the individual segments (including the decimal point), with a ninth connection common shared by the cathodes. The arrangement in Fig.4.3(b) is similar but the anodes and cathodes have been interchanged. The important difference between these two configurations is that the polarity of the common connection changes according to the display type. A common-cathode connection is returned to the common negative rail (usually GND) whereas a common-

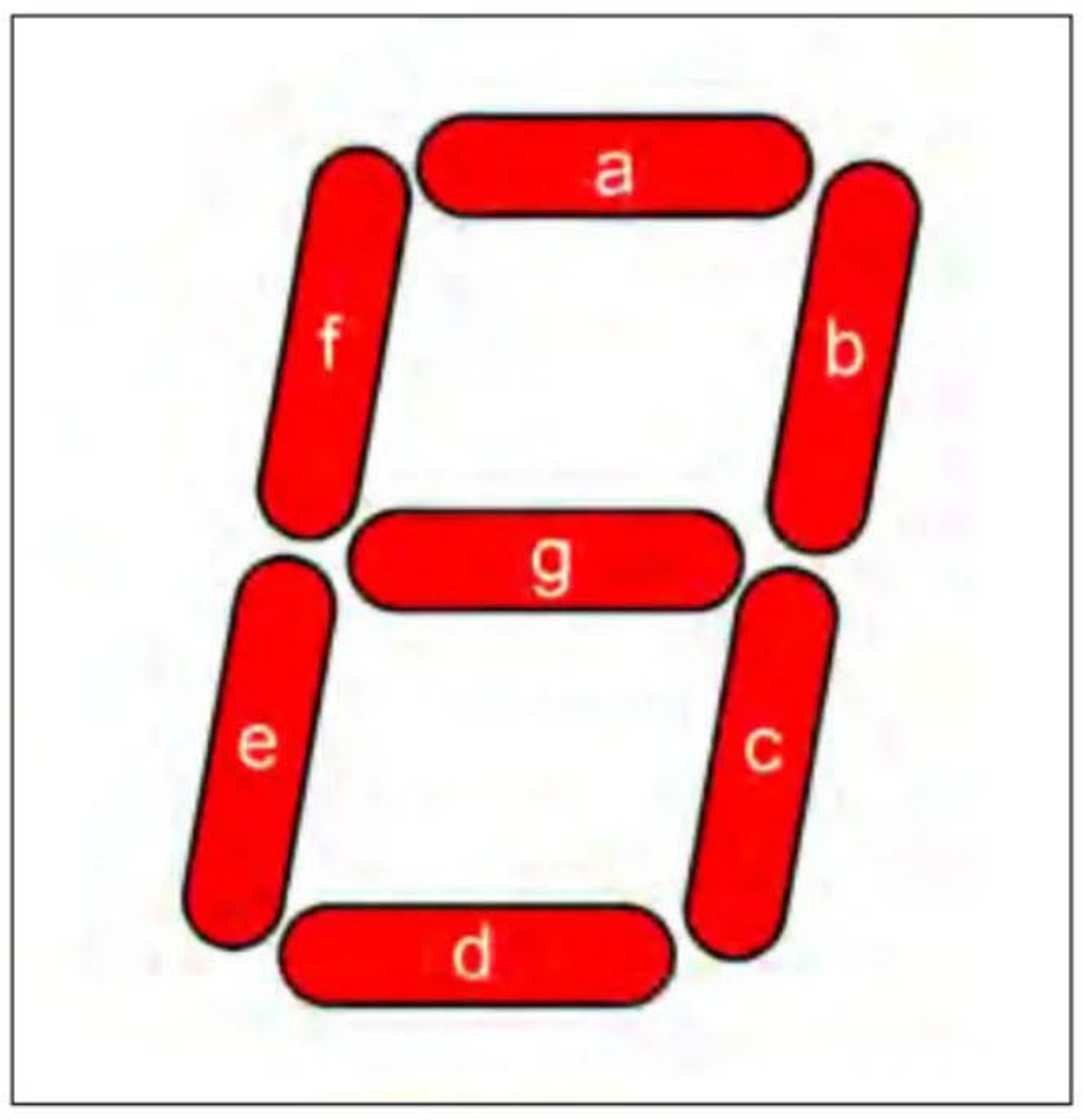
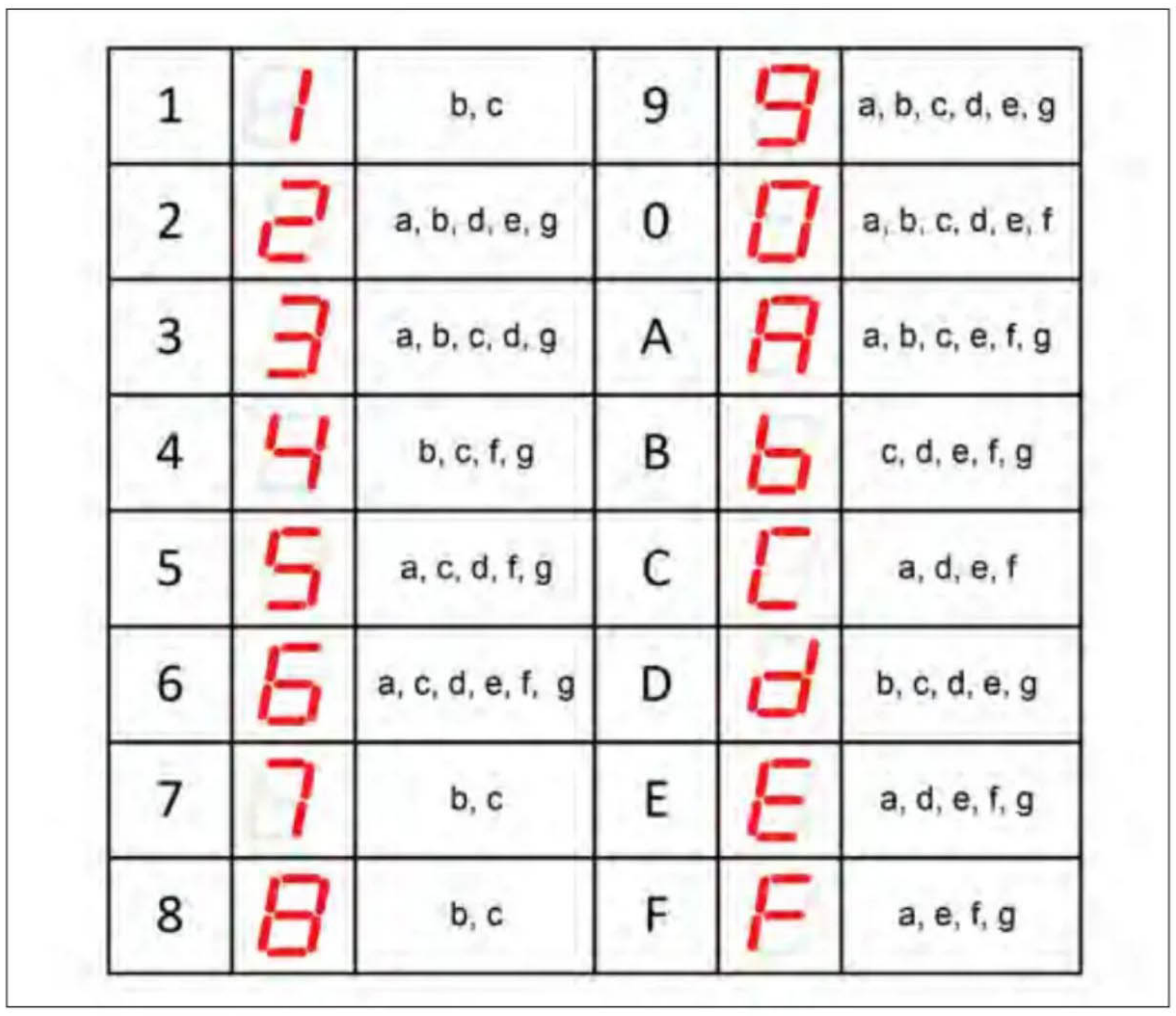
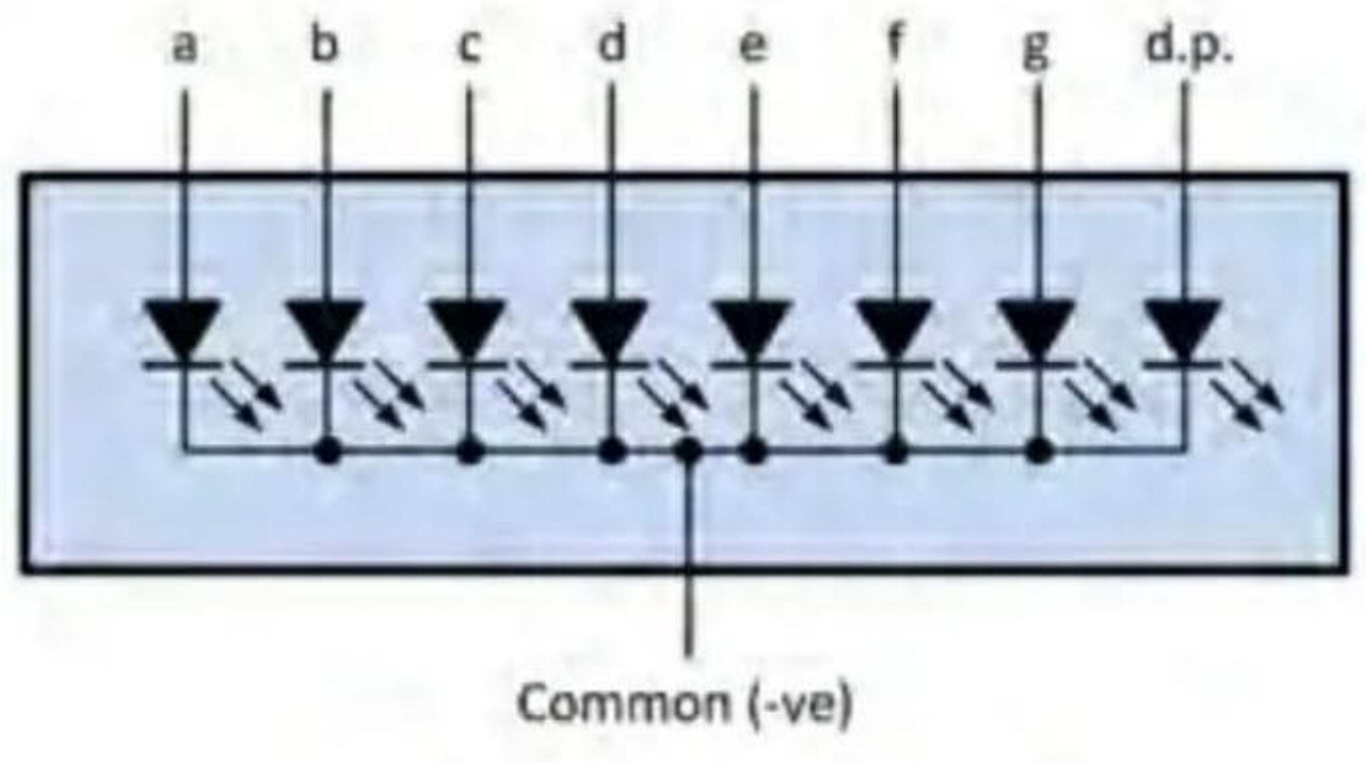


Fig.4.1 Segment labelling in a typical seven-segment LED display.

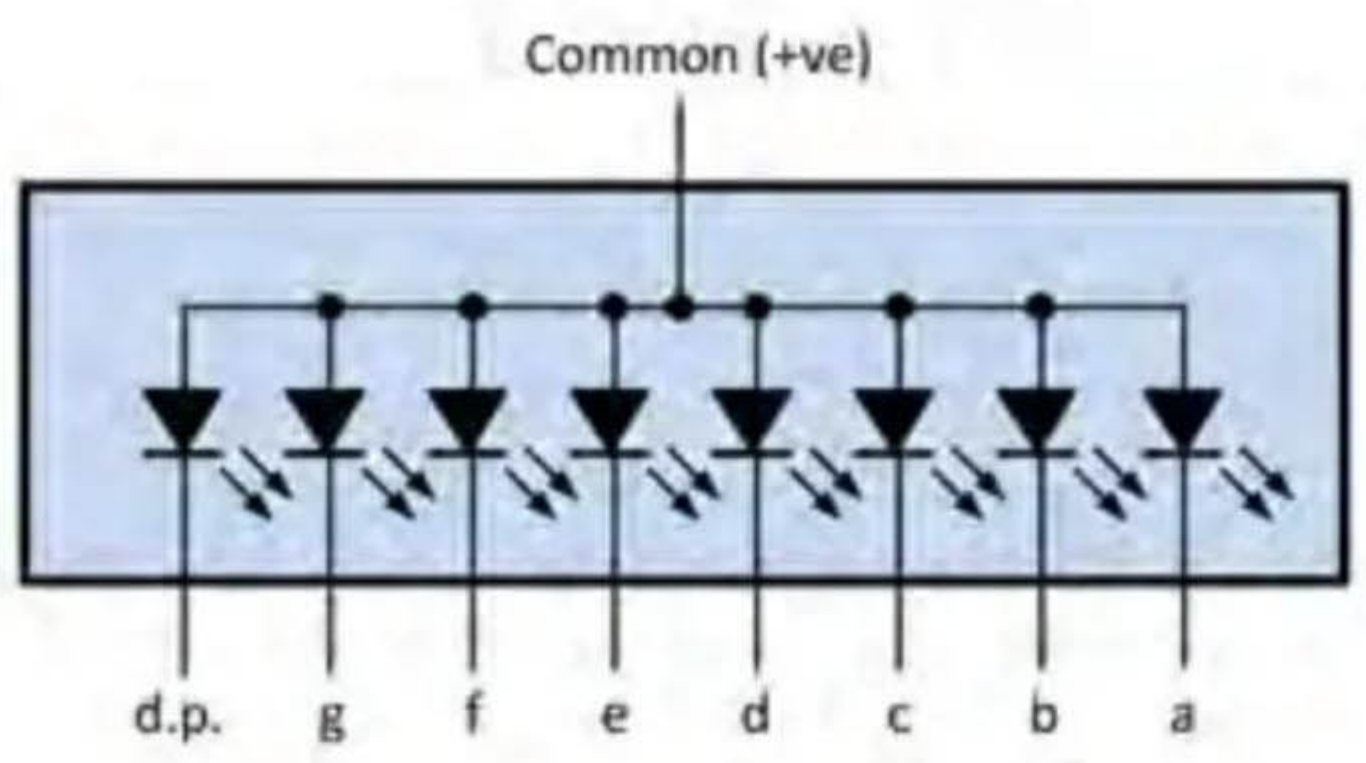


1	1	b, c	9	9	a, b, c, d, e, g
2	2	a, b, d, e, g	0	0	a, b, c, d, e, f
3	3	a, b, c, d, g	A	A	a, b, c, e, f, g
4	4	b, c, f, g	B	b	c, d, e, f, g
5	5	a, c, d, f, g	C	C	a, d, e, f
6	6	a, c, d, e, f, g	D	d	b, c, d, e, g
7	7	b, c	E	E	a, d, e, f, g
8	8	b, c	F	F	a, e, f, g

Fig.4.2 Hexadecimal numbers displayed using a seven-segment LED display.



(a) Common cathode



(b) Common anode

Fig.4.3 Common-cathode and common-anode LED displays.

anode connection is invariably taken to the common positive rail (usually VCC).

Check it out!

To interface a single seven-segment display to an ESP32 you will need eight connections, but an extra connection will be required if you are using the decimal point. Fig.4.4 shows how this is done using a common-cathode display. Seven series resistors (R1 to R7) each of 330Ω are used to limit the individual segment currents to a few mA. Note that when all the segments are illuminated you will need to be aware of the total load on the ESP32 and its power source. In the case of battery-operated equipment, you may find it necessary to limit the individual segment currents to less than about 10mA. A series resistance of 330Ω should suffice for most low-power applications yet still produce a reasonably bright display.

Typical display connections for a common-cathode seven-segment display are shown in Fig.4.5. Note that there are two 0V pins. These are the common connections, and they will normally be taken to GND. Fig.4.6 shows the breadboard wiring.

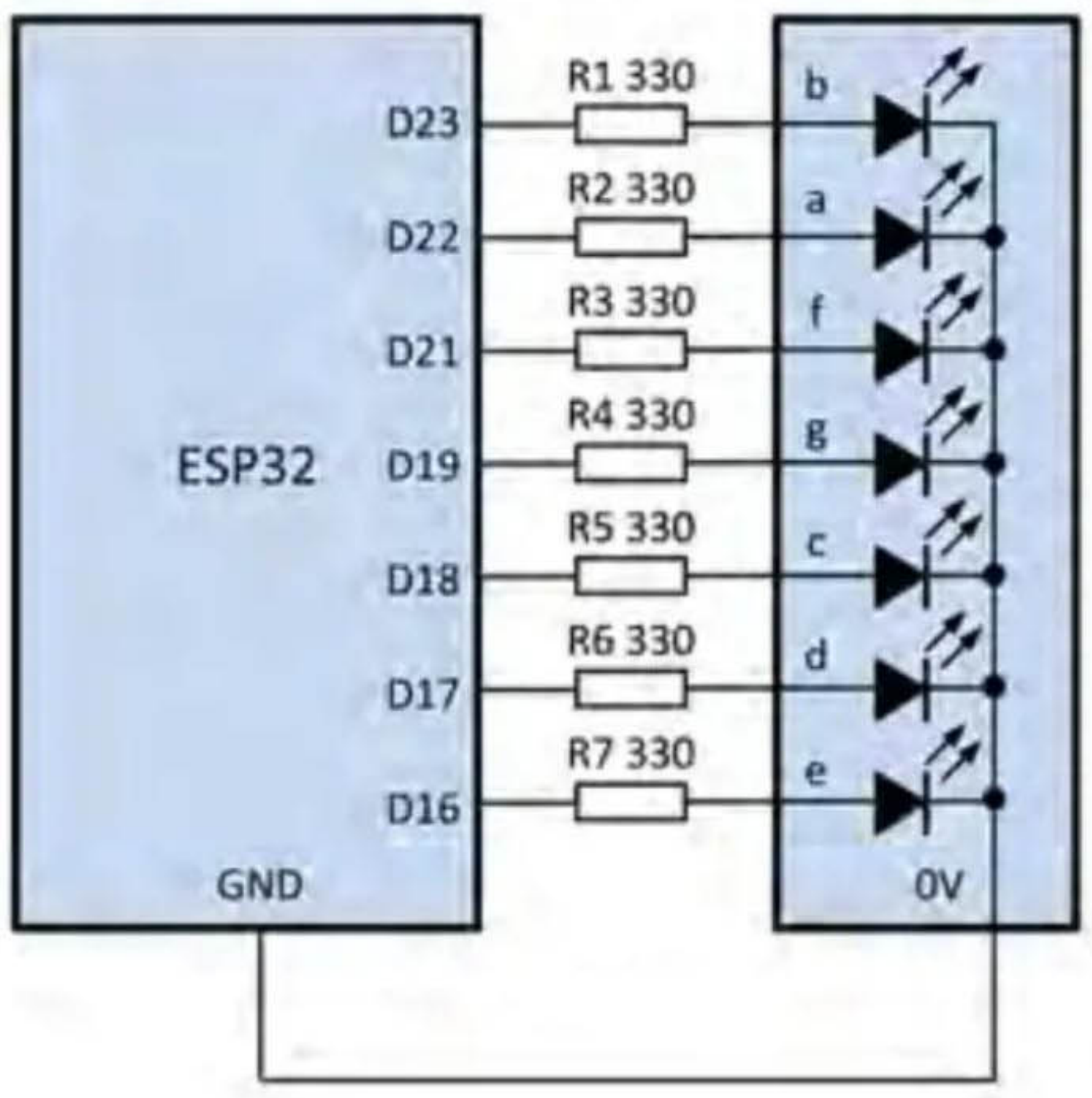


Fig.4.4 Interfacing an individual seven-segment LED display to an ESP32.

Gotcha!

Seven-segment displays come in two basic types: common-anode and common-cathode types. Since they are outwardly identical it's important to ensure that you are using the correct type.

Sample code for driving the seven-segment display is shown below in Listing 4.1. This code simply displays each number from 1 to (1)0 with the display held for a period defined by `delayTime()`. Note that the time delay is initialised to one second (1000ms) at the beginning of the code.

Listing 4.1 Seven-segment LED counter

```
/* Counter based on a single common
cathode seven-segment LED display */

// Assign display segments to GPIO pins
int a = 22;
int b = 23;
int c = 18;
int d = 17;
int e = 16;
int f = 21;
int g = 19;

// Set delay between counts
int delayTime = 1000;  // 1 second

void setup() {
// Initialise GPIO pins as outputs
pinMode(a, OUTPUT);     // Segment a
pinMode(b, OUTPUT);     // Segment b
pinMode(c, OUTPUT);     // Segment c
pinMode(d, OUTPUT);     // Segment d
   pinMode(e, OUTPUT);  // Segment e
   pinMode(f, OUTPUT);  // Segment f
   pinMode(g, OUTPUT);  // Segment g
}

void loop() { // Repeat forever
   // 1 => b,c
   digitalWrite(a, LOW);
   digitalWrite(b, HIGH);
   digitalWrite(c, HIGH);
   digitalWrite(d, LOW);
   digitalWrite(e, LOW);
   digitalWrite(f, LOW);
   digitalWrite(g, LOW);
   delay(delayTime);
   // 2 => a,b,d,e,g
   digitalWrite(a, HIGH);
   digitalWrite(b, HIGH);
   digitalWrite(c, LOW);
   digitalWrite(d, HIGH);
   digitalWrite(e, HIGH);
   digitalWrite(f, LOW);
   digitalWrite(g, HIGH);
   delay(delayTime);
   // 3 => a,b,c,d,g
   digitalWrite(a, HIGH);
   digitalWrite(b, HIGH);
   digitalWrite(c, HIGH);
   digitalWrite(d, HIGH);
   digitalWrite(e, LOW);
   digitalWrite(f, LOW);
   digitalWrite(g, HIGH);
   delay(delayTime);
   // 4 => b,c,f,g
   digitalWrite(a, LOW);
   digitalWrite(b, HIGH);
   digitalWrite(c, HIGH);
   digitalWrite(d, LOW);
   digitalWrite(e, LOW);
   digitalWrite(f, HIGH);
   digitalWrite(g, HIGH);
   delay(delayTime);
   // 5 => a,c,d,f,g
   digitalWrite(a, HIGH);
   digitalWrite(b, LOW);
   digitalWrite(c, HIGH);
   digitalWrite(d, HIGH);
   digitalWrite(e, LOW);
   digitalWrite(f, HIGH);
   digitalWrite(g, HIGH);
   delay(delayTime);
   // 6 => a,c,d,e,f,g
   digitalWrite(a, HIGH);
   digitalWrite(b, LOW);
   digitalWrite(c, HIGH);
   digitalWrite(d, HIGH);
   digitalWrite(e, HIGH);
   digitalWrite(f, HIGH);
   digitalWrite(g, HIGH);
   delay(delayTime);
   // 7 => a,b,c
   digitalWrite(a, HIGH);
   digitalWrite(b, HIGH);
   digitalWrite(c, HIGH);
   digitalWrite(d, LOW);
   digitalWrite(e, LOW);
   digitalWrite(f, LOW);
   digitalWrite(g, LOW);
   delay(delayTime);
   // 8 => a,b,c,d,e,f,g
   digitalWrite(a, HIGH);
   digitalWrite(b, HIGH);
   digitalWrite(c, HIGH);
   digitalWrite(d, HIGH);
   digitalWrite(e, HIGH);
   digitalWrite(f, HIGH);
   digitalWrite(g, HIGH);
   delay(delayTime);
   // 9 => a,b,c,d,f,g
   digitalWrite(a, HIGH);
   digitalWrite(b, HIGH);
   digitalWrite(c, HIGH);
   digitalWrite(d, HIGH);
   digitalWrite(e, LOW);
   digitalWrite(f, HIGH);
   digitalWrite(g, HIGH);
   delay(delayTime);
   // 0 => a,b,c,d,e,f
   digitalWrite(a, HIGH);
   digitalWrite(b, HIGH);
   digitalWrite(c, HIGH);
   digitalWrite(d, HIGH);
   digitalWrite(e, HIGH);
   digitalWrite(f, HIGH);
   digitalWrite(g, LOW);
   delay(delayTime);
}
```

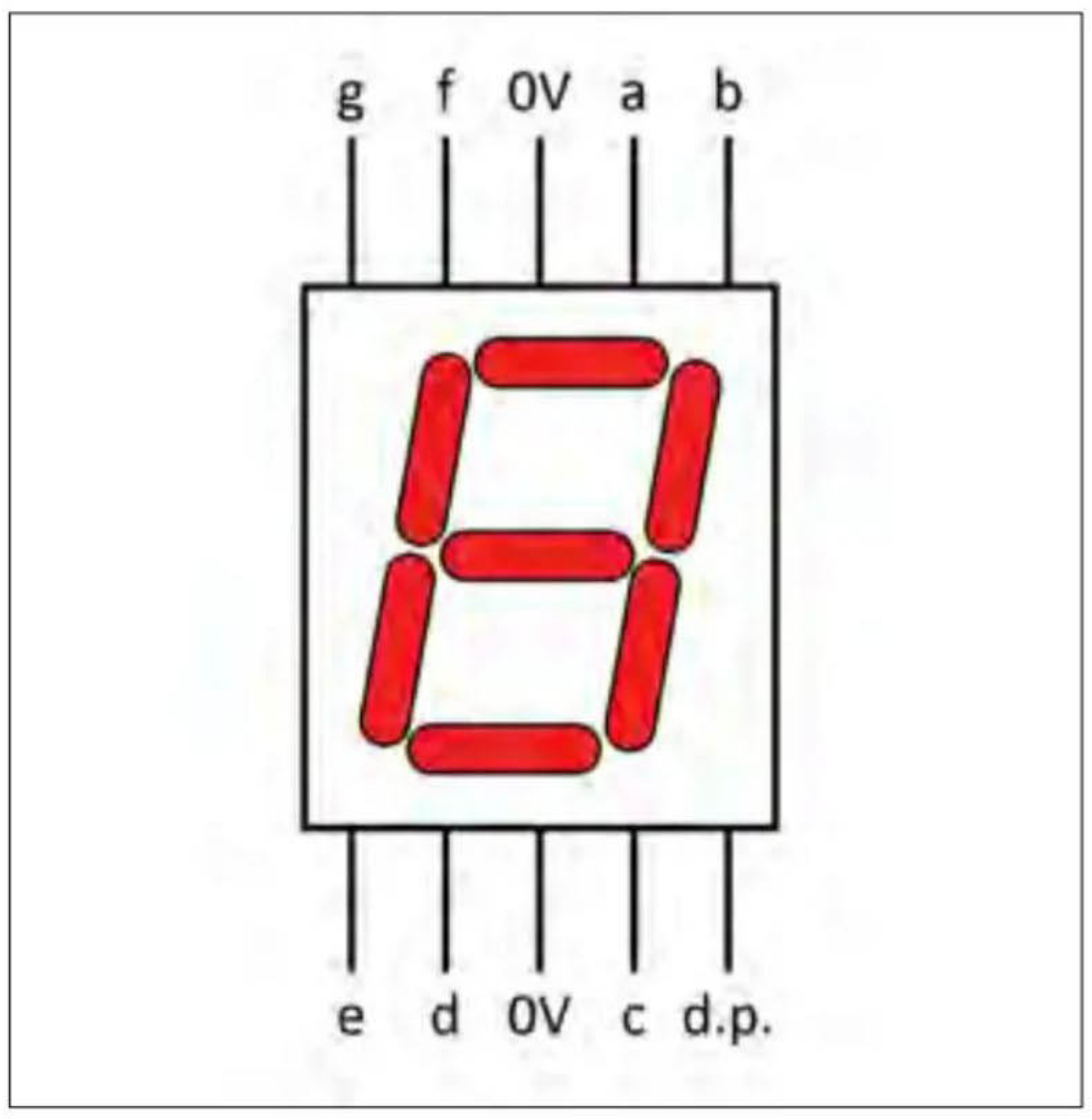


Fig.4.5 Typical pin connections for a common-cathode seven-segment LED display.

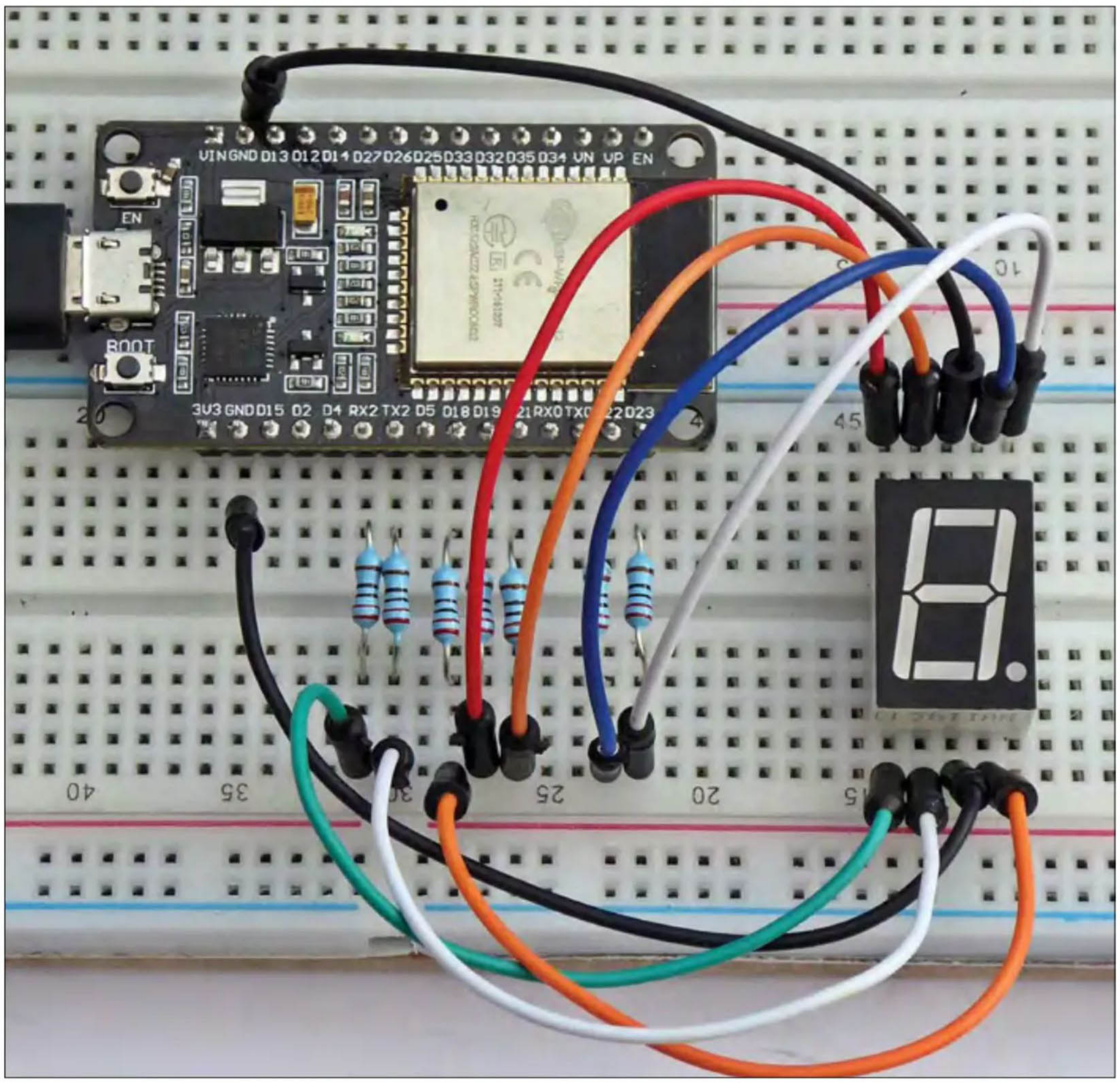


Fig.4.6 Breadboard wiring for the ESP32 and common-cathode seven-segment display.

We've liberally commented the code in Listing 4.1 to make it easy to follow. Note that, as with all our code examples, we've not attempted to oversimplify the code nor present it in minimal form. Instead, we've tried to make it as clear and unambiguous as possible. As you become more proficient with coding you will undoubtedly be able to improve on our efforts and produce something more compact.

Using seven-segment display modules

If you've checked out our simple seven-segment counter, you might want to interface more than one display and be wondering if there's a better way of doing things. The answer is, of course, yes there is!

If you need multiple seven-segment displays with the segments addressed along the lines of our previous example, then this can quickly become extremely cumbersome – just imagine interfacing a counter/timer with 10 or 12 seven-segment displays! Furthermore, if you have more than two seven-segment displays you will start to run out of GPIO pins. Fortunately, there's a simple solution based on one or more external driver devices. These are often packaged along with a two-, four-, or eight-digit display and require only four connections to the ESP32, as shown in Fig.4.7. So, having shown you a rather clumsy method of interfacing a seven-segment display to the ESP32 let's now move on to a much-improved way of interfacing a multi-digit display.

In the arrangement shown in Fig.4.7 just four connections are needed to drive a total of 30 display segments. The connections required are: VCC to the ESP32's +5V supply, DIO to D23 on the ESP32, CLK to D22 on the ESP32, and last, but not least, GND to GND.

4-digit display implementation

The required breadboard wiring for checking out a 4-digit display module is shown in Fig.4.8. If you compare this with Fig.4.6 you will see just how much neater this is. The display module uses a serial interface to the ESP32 based on a cTM1637 driver chip. This device does all the hard work, leaving you to concentrate on getting the best out of it.

Since we have four digits to play with, we will use them to develop a timer that produces a display of minutes (the two left-most digits) and seconds (the two right-most digits). To ensure accuracy of the timing, we've decided not to use the ESP32's `delay()` function. Instead, we will be using the ESP32's real-time clock (RTC). To make use of the TMD1637 and the ESP32's RTC we will need to include two library routines in our code. If you refer to

Listing 4.2 Minutes and seconds counter using a TM1637 serial interface and the ESP32's RTC

```
/* Minutes and seconds counter using ESP32 RTC,
TM1637 driver and LED display. Time initialised
to 00:00:00 for use with a 4-digit LED display. */

#include <ESP32Time.h>
#include <TM1637Display.h>
#define CLK 22  // GPIO22 to CLK on the TM1637
#define DIO 23  // GPIO23 to DIO on the TM1637

// Set up RTC and display
ESP32Time rtc(3600);  //  Seconds offset for GMT+1
TM1637Display display = TM1637Display(CLK, DIO);

void setup() {
   display.clear();
   display.setBrightness(7);  // Set display brightness
   rtc.setTime(1609459200);   // Set RTC to Jan 2021 00:00:00
}

void loop() {
   int time;
   struct tm timeinfo = rtc.getTimeStruct();
   time = (rtc.getMinute() * 100) + (rtc.getSecond());
   display.showNumberDecEx(time, 0b11100000, true, 4, 0);
   delay(1000);  // Wait one second
}
```

Listing A – code fragment

```
// Generate random numbers in the range 1 to 9

long randomValue;

void setup() {
   Serial.begin(9600);
   // Uncomment next line to use a random seed
   // randomSeed(analogRead(0));
}

void loop() {
   randomValue = random(1, 10);
   Serial.print(randomValue);
   Serial.print(“ “);
   delay(1000);
}
```

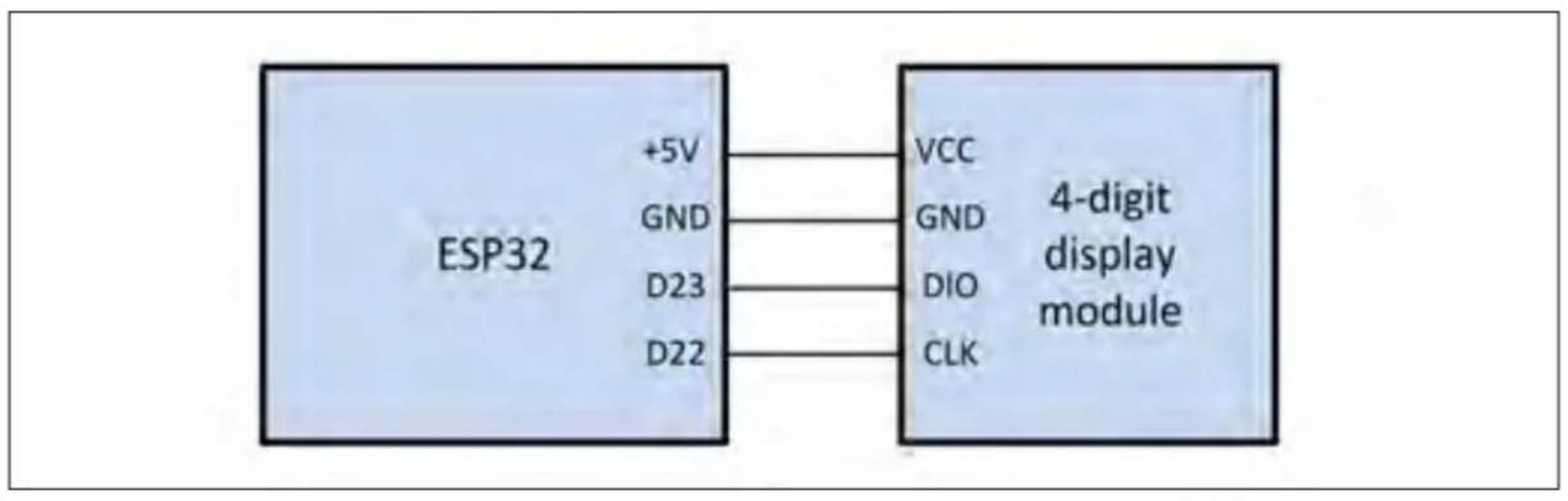


Fig.4.7 Interfacing a 4-digit seven-segment LED display module to an ESP32.

Listing 4.2 you will see the two lines of code that do this:

```
#include <ESP32Time.h>  // To use the ESP32's RTC

#include <TM1637Display.h>  // To use the TM1637
```

If you don't have these library files installed they can be quickly and easily downloaded from within the Arduino IDE. Just search for the file that you need using the Library Manager.

Coding Workshop

For applications such as games and password generators you might sometimes find that you need to generate random numbers. Unfortunately, this can be something of a problem in a microcomputer environment where nothing occurs that can ever be described as truly random. To meet this need the ESP32's C++ language includes the `random()` function. that generates values that although not truly random in a strict mathematical sese can at least be considered to be usefully 'pseudo random'. Let's suppose that you need a random integer in the range 1 (minimum) to 9 (maximum). The following line of code would do the trick:

```
randomValue = random(1, 10);
```

Note that we would need to have previously defined `randomValue` as a variable using a line of the form:

```
long randomValue;
```

To improve the randomness of the values returned from `random()` it's possible to change the seed that's used by the function (otherwise the random number generator will always use the same seed value). There's a rather neat way of doing this.

The noise present on any of the ESP32's analogue inputs is inherently random in nature and the voltage read from an unconnected analogue pin will also be random. So, to seed the random number generator from the voltage present on analogue input A0 you would just need to add the following line of code:

```
randomSeed(analogRead(0));
```

Listing A shows a fragment of code that will allow you to check this for yourself. Note that when you've successfully compiled and uploaded the code you will need to start the Serial Monitor after execution to see the values produced.

Now for a second example (Listing B) using the `random()` function in the form of a random HEADS and TAILS generator. This time we are only interested in random numbers in the range 0 and 1, where 0 will display a TAILS result, and 1

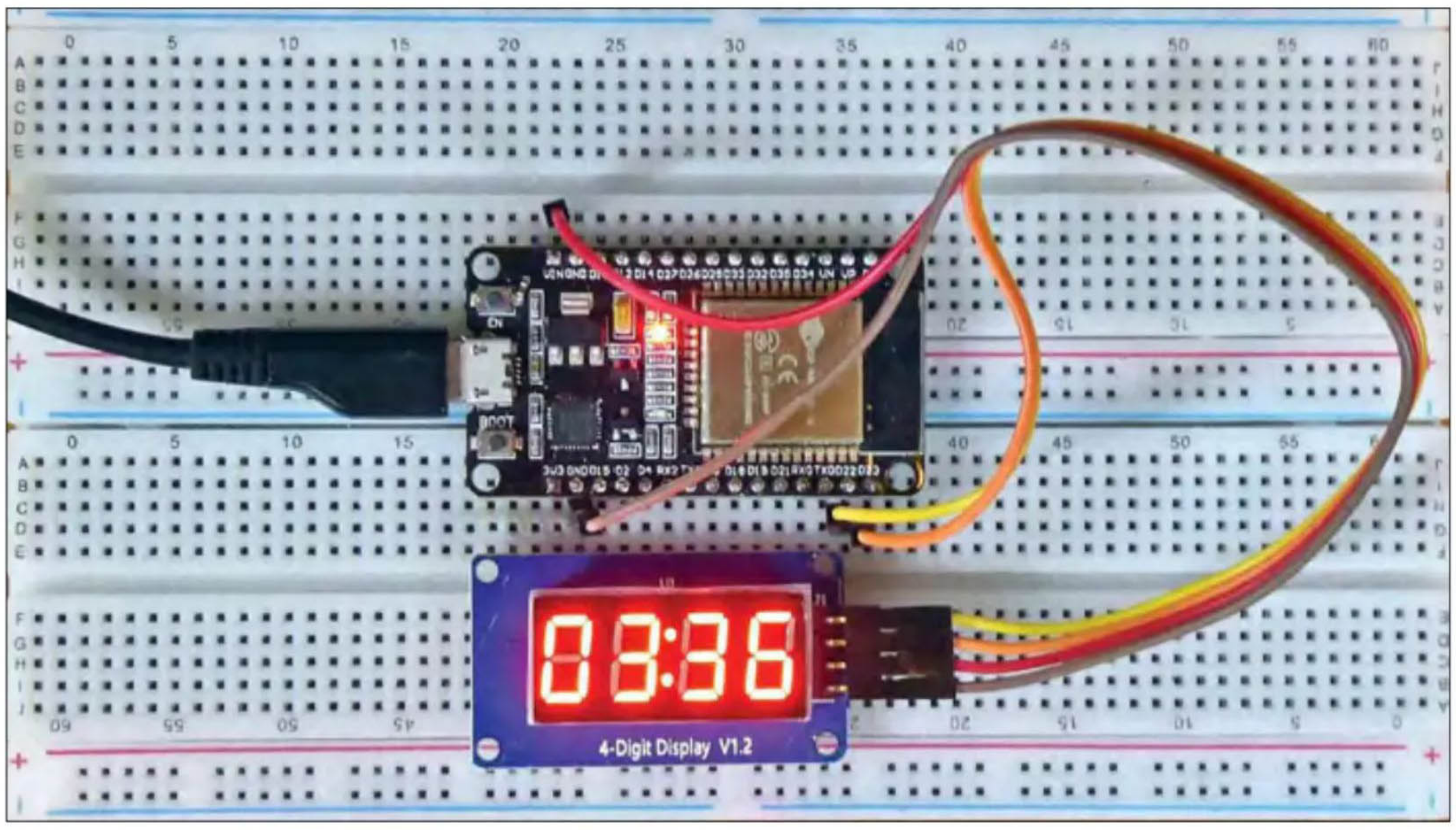


Fig.4.8 Breadboard wiring for the ESP32 and 4-digit seven-segment LED display module.

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Listing B – code fragment

```
// Coin toss producing random HEADS and TAILs

long randomValue;

void setup() {
   Serial.begin(9600);
   // Uncomment next line to use a random seed
   // randomSeed(analogRead(0));
}

void loop() {
   randomValue = random(0, 2);
   if (randomValue == 1) {
        Serial.print(“HEADS “);
   } else {
        Serial.print(“TAILS “);
   }
   delay(1000);
}
```

Gotcha!

If you find that the Serial Monitor displays gobbledygook instead of a series of meaningful values, you should first check that you have set a baud rate that matches the speed that you've specified in your code. Our previous two examples operate at 9600 baud. To work correctly this *must* match the value that you have set in the Serial Monitor.

will produce HEADS. Once again, you will need to run the Serial Monitor to check the results.

Using matrix LED displays

Having experimented with seven-segment displays let's now move on to a different and more flexible type of LED display based on a matrix of individual LEDs. The most common types of small LED matrix display are based on an 8×8 LED array, as shown in Fig.4.9.

To reduce the number of connections between the display's 64 LEDs and the outside world, the diodes are arranged in an array of eight rows (R1 to R8) and eight columns (C1 to C8). With this configuration individual diodes can be addressed by referencing the rows and columns in which they are placed. In Fig.4.9 we've shown how two of the LEDs (referenced by R3/C5 and R5/C3) can be illuminated by a current of typically 5 to 15mA.

Gotcha!

The maximum random value generated by `random()` is one less than the function's second parameter. For example, to generate six different random numbers in the range 1 to 6 (for example, the faces on dice) the function would need to be `random(1, 7)` not `random(1, 6)`. This may sound obvious but it is often forgotten.

Table 4.1 ESP32 SPI implementation

Designation	Function	Direction	VSPI pin number	HSPI pin number
SCLK	Serial clock	Output from ESP32	18	14
MOSI	Master output/slave input	Output from ESP32	23	13
MISO	Master input/slave output	Input to ESP32	19	12
CS	Chip select	Output from ESP32	5	15
GND	Ground	Common	GND	GND

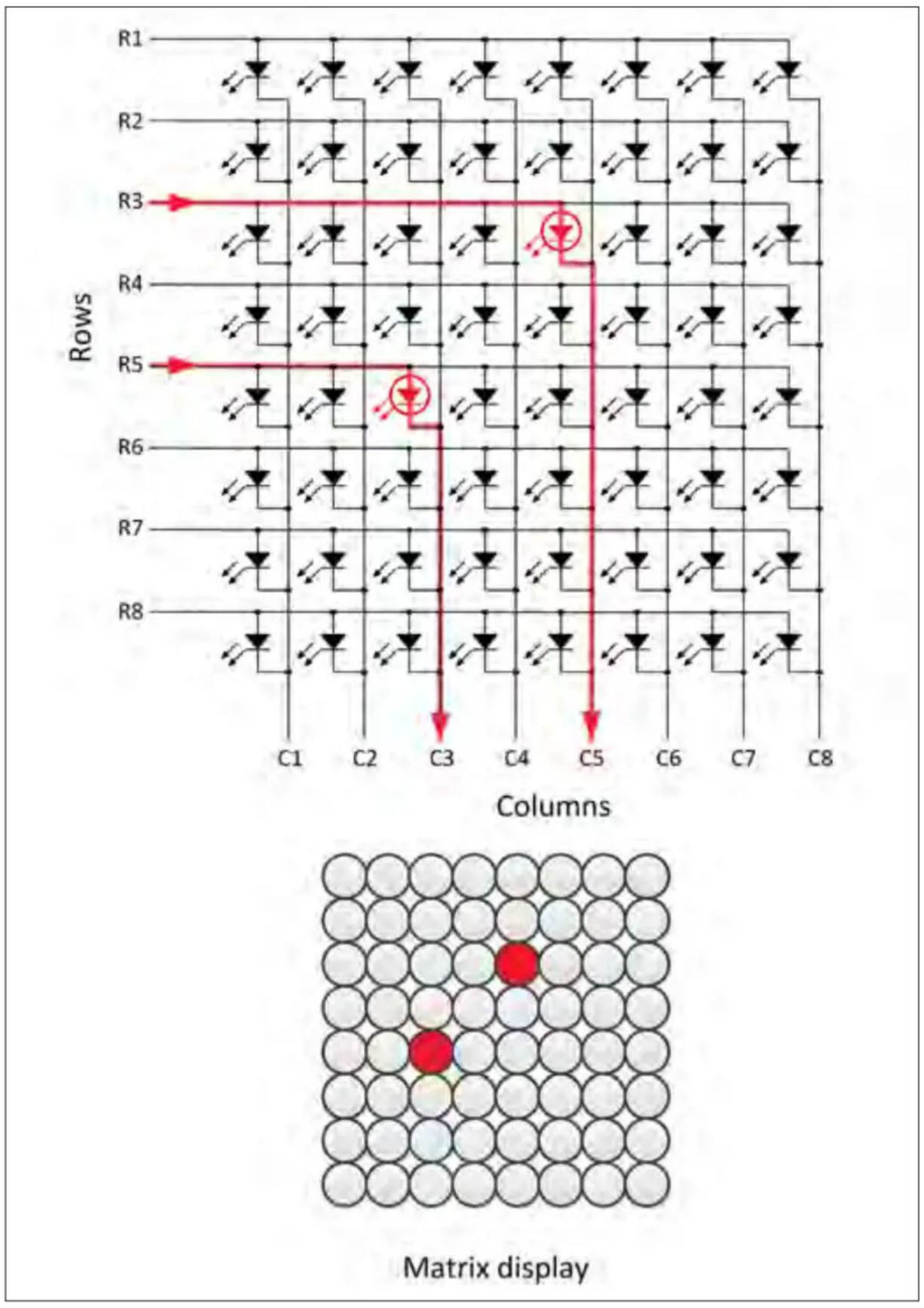

Fig.4.9 Basic arrangement of an 8×8 LED matrix display.

Fig.4.10 shows how a typical 8×8 LED matrix display appears when the following LEDs are addressed:

R1/C3, R1/C4, R1/C5, R1/C6, R2/C2, R2/C3, R2/C6,
R2/C7, R3/C7, R4/C6, R4/C7, R5/C5, R5/C6, R6/C4,
R6/C5, R8/C4, R8/C5.

In case this is beginning to look overcomplicated, the problem of addressing the necessary LED to display a particular set of text characters is solved for you. You just need to use the right library!

The interface to an LED matrix display is usually based on a de facto standard known as Serial Peripheral Interface (SPI). SPI supports serial communication between a 'master' (the ESP32) and a 'slave' (the matrix display).

The Serial Peripheral Interface (SPI)

SPI is a communication standard that's used to interface one or more peripheral devices (known as 'slaves') to a microprocessor or microcontroller (referred to as the 'master'). A wide

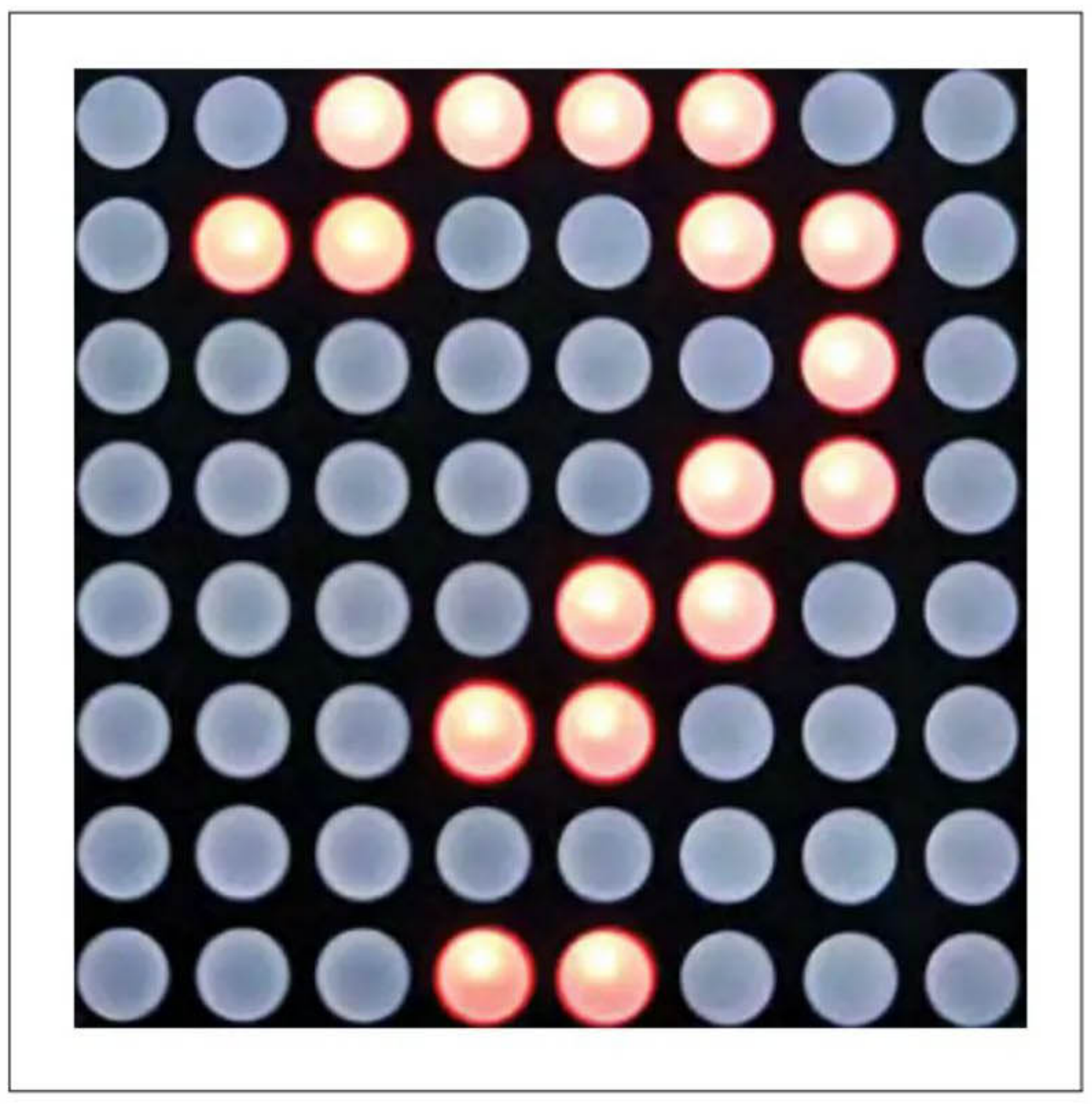

Fig.4.10 An 8×8 LED matrix display.

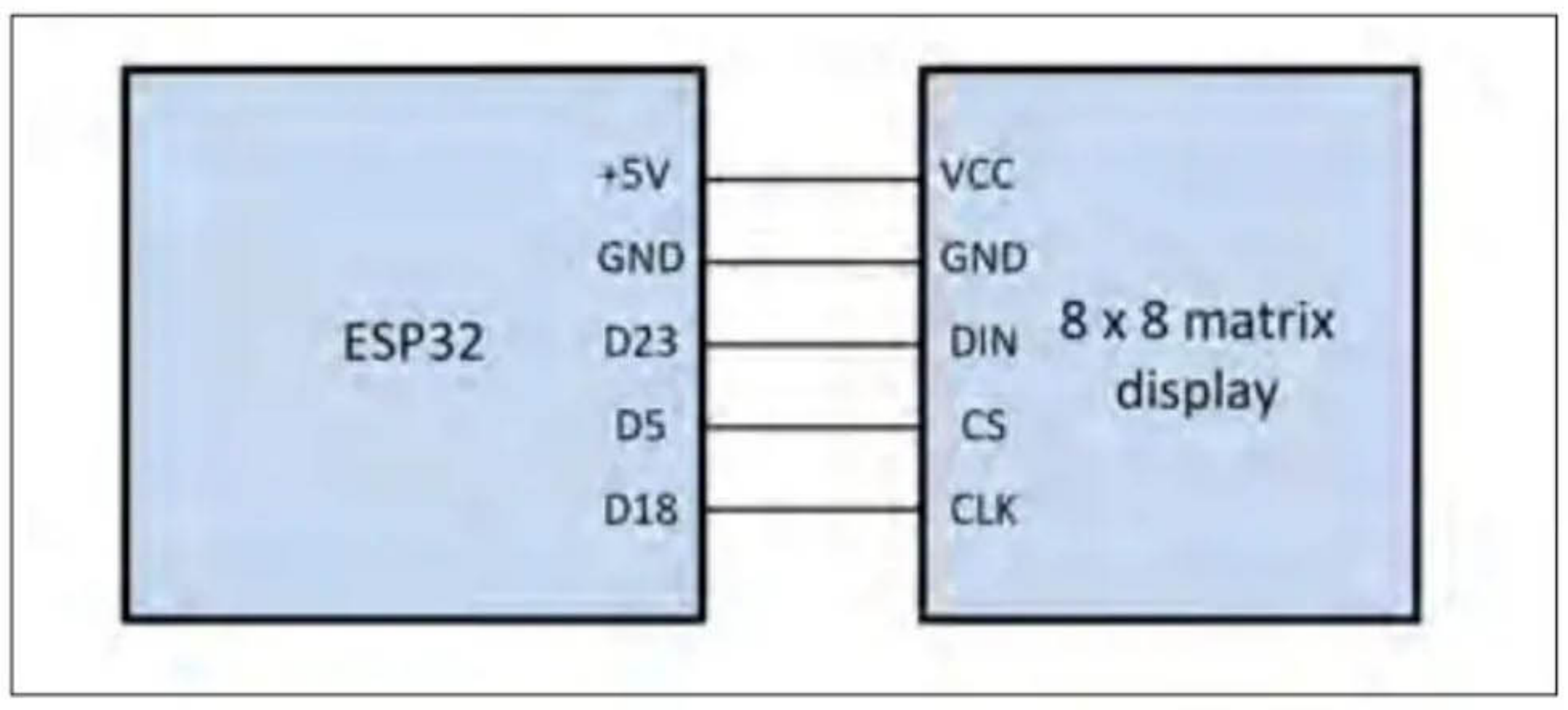

Fig.4.11 Using SPI to interface a single 8×8 LED matrix display to an ESP32.

Gotcha!

ESP32 development boards usually have SPI pins pre-assigned along the lines shown in Table 4.1. If you are using a different type of platform for developing your application and plan on using SPI then it is important to check the pin assignment before use.

variety of SPI-compatible devices are available, and we will be introducing several of them in this *Teach-In* series. They include displays (both LED and LCD types), ADCs and DACs, as well as temperature sensors, accelerometers and GPIO expansion chips. The SPI bus is capable of operating at high speed over short distances and it normally requires a four-wire connection with a chip select (CS) connection dedicated to each peripheral SPI device.

The SPI bus is a synchronous (serial clocked) interface capable of supporting data transfer in both directions, master to slave and slave to master, at the same time – this is referred to as 'full duplex' operation. The ESP32's SPI implementation uses four signal wires (plus ground). These are listed in Table 4.1 together with the pin connections conventionally used on ESP32 development boards.

The ESP32 is capable of handling four peripheral devices connected using the SPI bus with two reserved for communicating with the built-in flash memory. This leaves two independent SPI channel for your use, VSPI and HSPI and each of these can drive up to a maximum of three external slaves.

The method of interfacing a single 8×8 LED matrix display to an ESP32 via SPI is shown in Fig.4.11. Here, five connections are needed to drive a total of 64 LED. The connections required are:

VCC to +5V supply for the ESP32
DIN to D23 on the ESP32
CLK to D18 on the ESP32
CS to D5 on the ESP32
GND to GND for the ESP32 (don't forget this one!).

Gotcha!

If you are connecting multiple SPI peripherals it is essential to ensure that each device has a unique chip select (CS) connection. Failure to observe this precaution will yield unpredictable results.

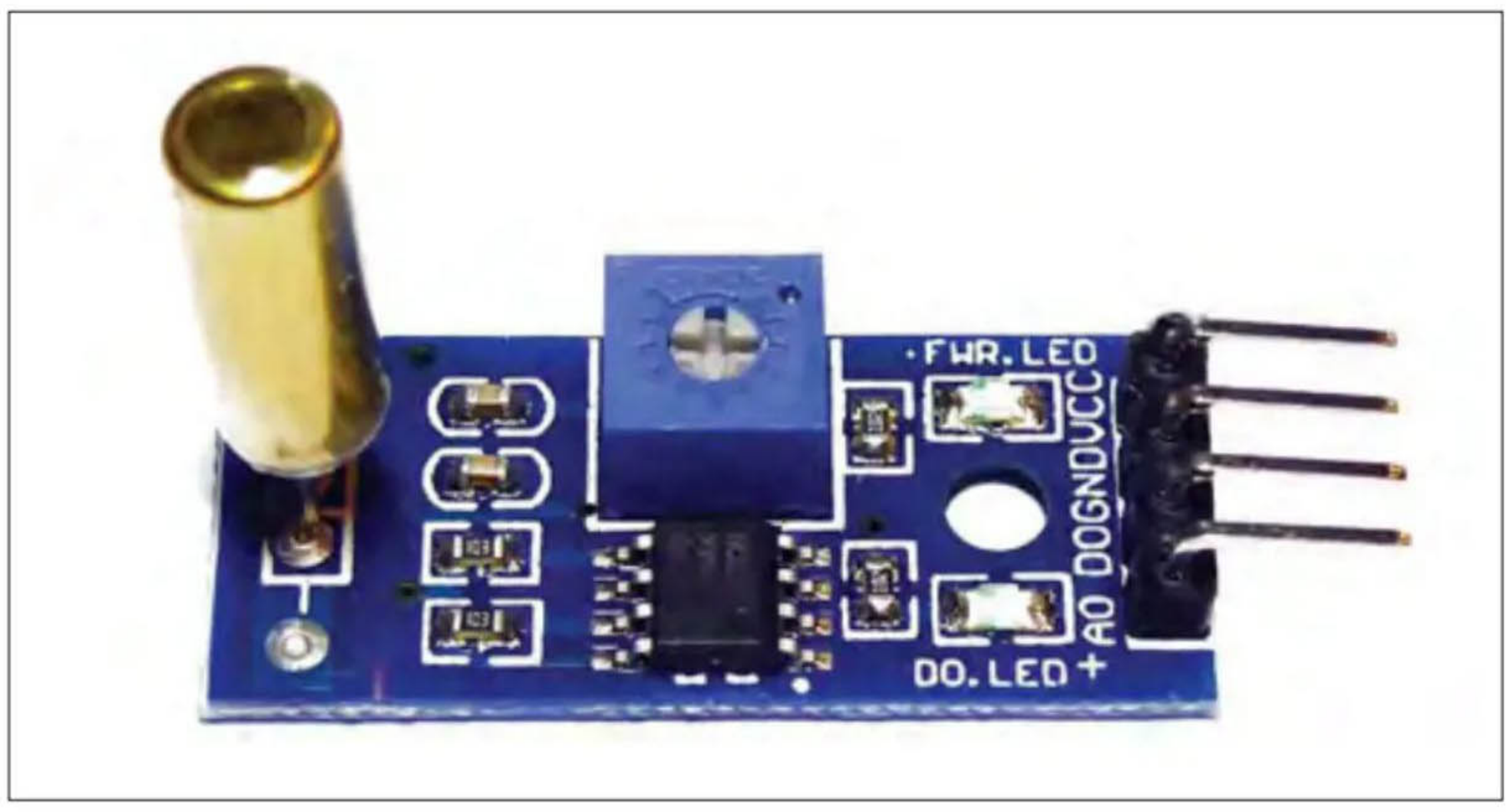

Fig.4.12 A low-cost motion sensor.

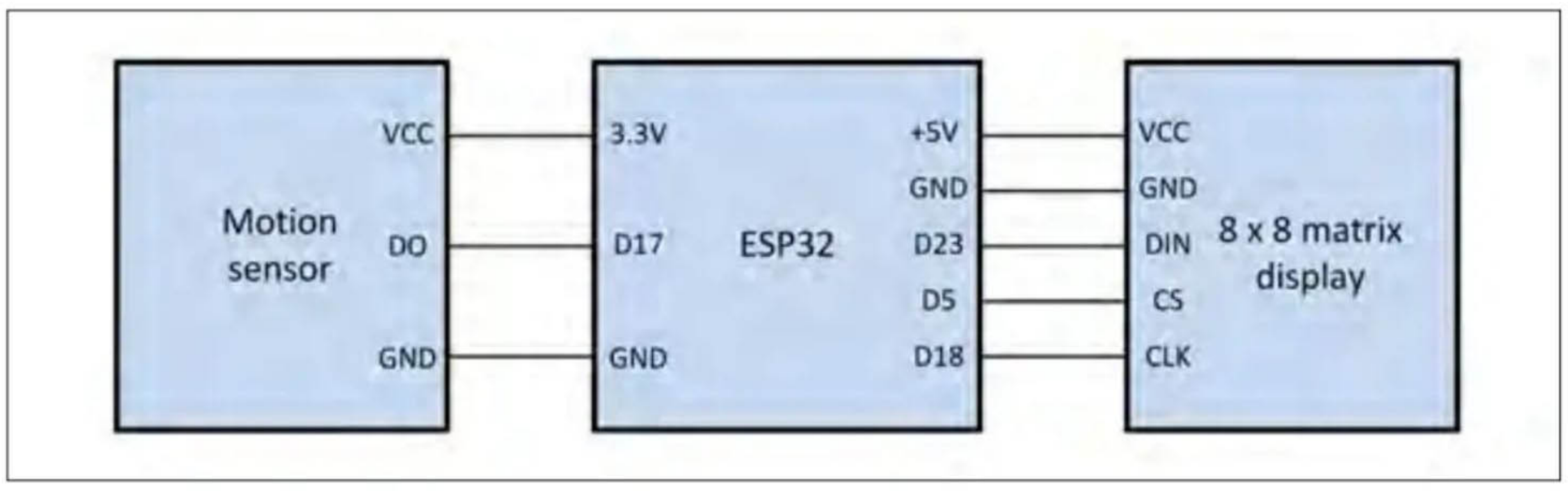

Fig.4.13 Circuit arrangement for the dice roller.

Practical Project

This month's *Practical Project* takes the form of a dice roller which comprises an ESP32, an 8×8 LED matrix display and a low-cost motion sensor (see Fig.4.12).

Listing 4.3 Dice roller code

```
/* Dice roller based on 8x8 LED matrix display
and motion sensor */
#include <MD_Parola.h>
#include <MD_MAX72xx.h>
#include <SPI.h>

// Uncomment depending on display type
// #define HARDWARE_TYPE MD_MAX72XX::FC16_HW
#define HARDWARE_TYPE MD_MAX72XX::GENERIC_HW

// Define display and I/O pins
#define MAX_DEVICES 1
#define CS_PIN 5
const int sensorPin = 17;
MD_Parola  Display  =  MD_Parola(HARDWARE_TYPE,
CS_PIN, MAX_DEVICES);

void setup() {
   Display.begin();
   Display.setIntensity(0);
   Display.displayClear();
   randomSeed(analogRead(27)); // Seed from noise
on pin 27
}

void loop() {
   // Wait for input from the motion sensor
   int sensorState = digitalRead(sensorPin);
   int lastSensorState;
   while (sensorState == lastSensorState) {
     sensorState = digitalRead(sensorPin);
     Display.setInvert(false);
     Display.setTextAlignment(PA_CENTER);
     Display.print(“?”);
   }

   // We have movement so roll it
   for (int i = 0; i < 10; i++) {
     Display.setInvert(true);
     Display.setTextAlignment(PA_CENTER);
     Display.print(“?”);
     delay(50);
     Display.setInvert(false);
     Display.setTextAlignment(PA_CENTER);
     Display.print(“?”);
     delay(50);
   }

   // And then display the result
   Display.setTextAlignment(PA_CENTER);
   Display.print(String(random(1, 7)));
   delay(2000);
   lastSensorState = sensorState;
}
```

Listing 4.4 Text message display using four 8×8 LED matrix displays

```
/* Text display using an ESP32 and four 8 x 8
matrix LED displays */

// Include the library files
#include <MD_Parola.h>
#include <MD_MAX72xx.h>
#include <SPI.h>

// Uncomment depending on display type
#define HARDWARE_TYPE MD_MAX72XX::FC16_HW
// #define HARDWARE_TYPE MD_MAX72XX::GENERIC_HW

// Define display and I/O pins
#define MAX_DEVICES 4
#define CS_PIN 5
MD_Parola Display = MD_Parola(HARDWARE_TYPE,
CS_PIN, MAX_DEVICES);

void setup() {
   // Intialise the display
   Display.begin();
   Display.setIntensity(0);
   Display.displayClear();
}

void loop() {
   Display.setTextAlignment(PA_CENTER);
   Display.print(“ON AIR”);
   delay(2000);
}
```

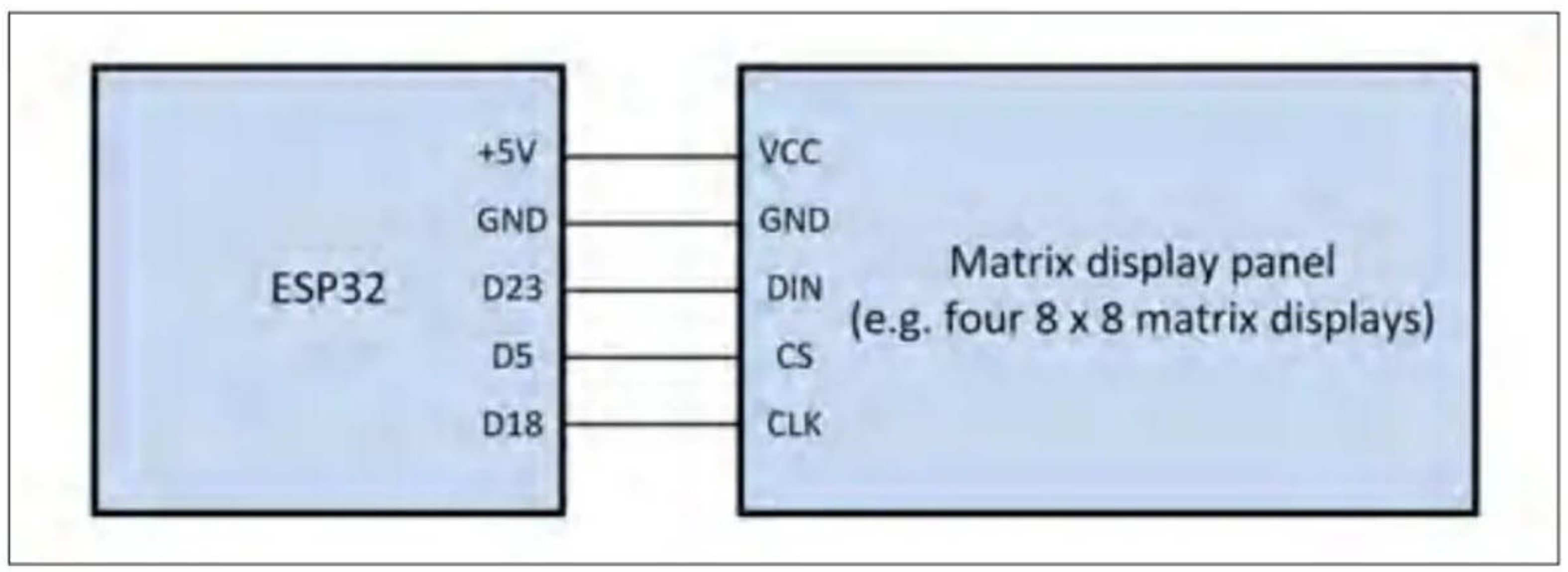

Fig.4.14 Arrangement for cascading multiple matrix displays.

When physical movement is detected by the motion sensor (a slight tap is usually enough) this produces a change of logic level on the DO pin and this in turn is used to break out of the `while()` loop in Listing 4.3. Note that we need to include three libraries at the beginning of the code. This is done with the aid of the following lines:

```
#include <MD_Parola.h> // To write text to the display

#include <MD_MAX72xx.h> // To use the MAX72xx driver

#include <SPI.h> // To use the SPI interface
```

Gotcha!

Large matrix displays can use a very large number of individual LED. For example, if four 8×8 displays are cascaded there will be a total of 256 LEDs present. If each of these LEDs is illuminated simultaneously (unlikely but not impossible) and if each is fed with a current of 10mA the total load on the ESP32 power supply will amount to more than 2.5A. This can easily exceed the capability of a standard USB port.

Note, that once again, you may need to locate and download the first two of these library files from within the Arduino IDE.

Fig.4.13 shows the interconnection of an LED matrix display, motion sensor and ESP32. We've not shown a full wiring diagram this time because the arrangement is straightforward, and you will doubtless have had plenty of experience with our two previous examples. Note that if the motion sensor has an analogue output (as well as a digital output) this can be ignored. The dice roller code is shown in Listing 4.3.

Displaying text messages

LED matrix displays can be easily cascaded to produce larger static and scrolling text displays. The arrangement in Fig.4.14 and code in Listing 4.4 shows how this can be done but note that the code must be changed to indicate the number of 8×8 displays that are present. This requires the following change to Listing 4.3:

```
#define MAX_DEVICES 4
```

instead of:

```
#define MAX_DEVICES 1
```

Teach-In Challenge

This month's *Teach-In Challenge* involves extending the hardware and modifying the code in Listing 4.4 to produce a door entry indicator which will display the messages 'WAIT' or 'ENTER' depending on the state of a push button switch connected to one of the ESP32's digital inputs. If you need help interfacing the switches look back at *Part 2* of our series.

Next month

In *Part 5* next month, we will introduce temperature and humidity sensing, delving into the popular 1-wire and I^{2}C interface standards, and explain how low-cost LCD displays can be added to your ESP32 projects. *Coding Workshop* will deal with mathematics operators and functions, and our *Practical Project* will feature a useful digital temperature and humidity monitor.

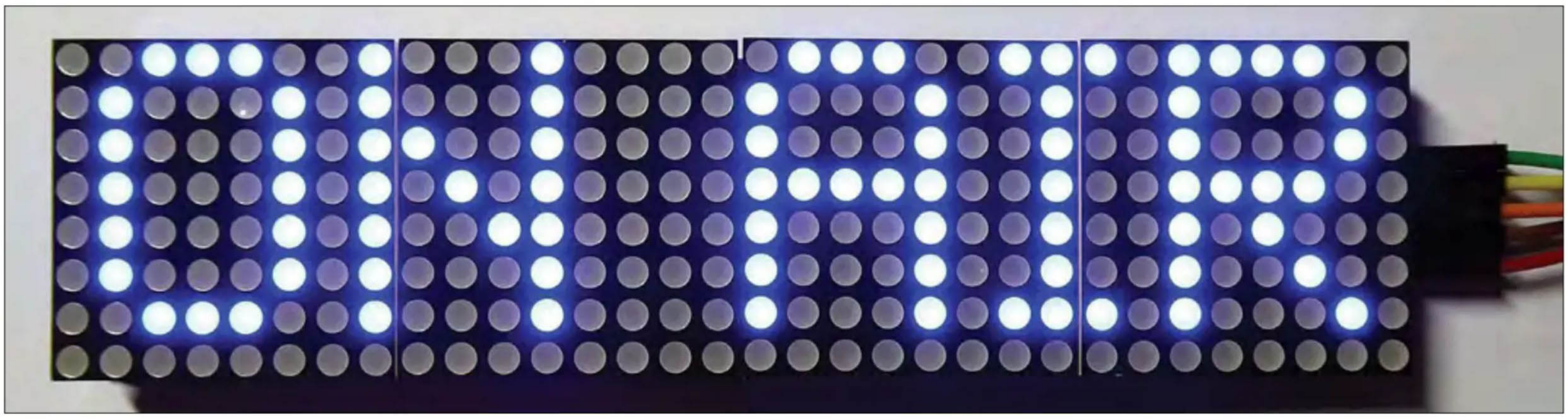

Fig.4.15 Text display produced by Listing 4.4.

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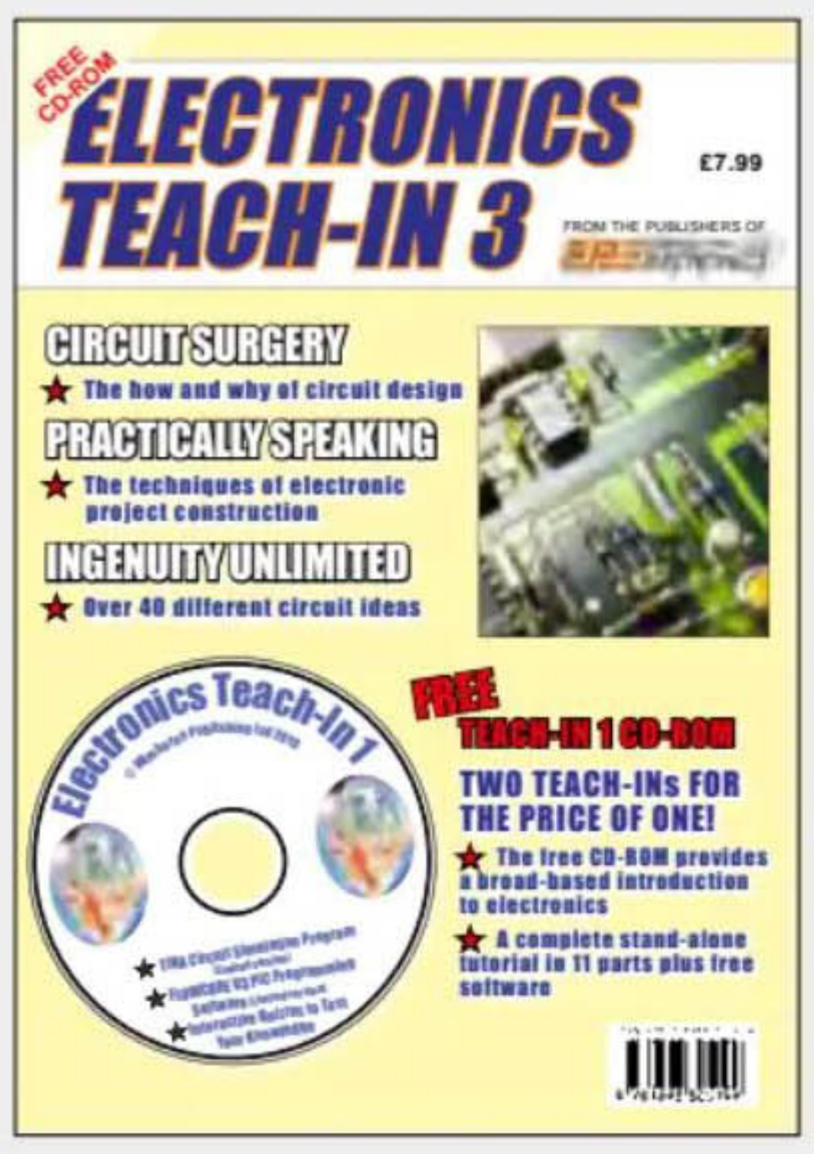

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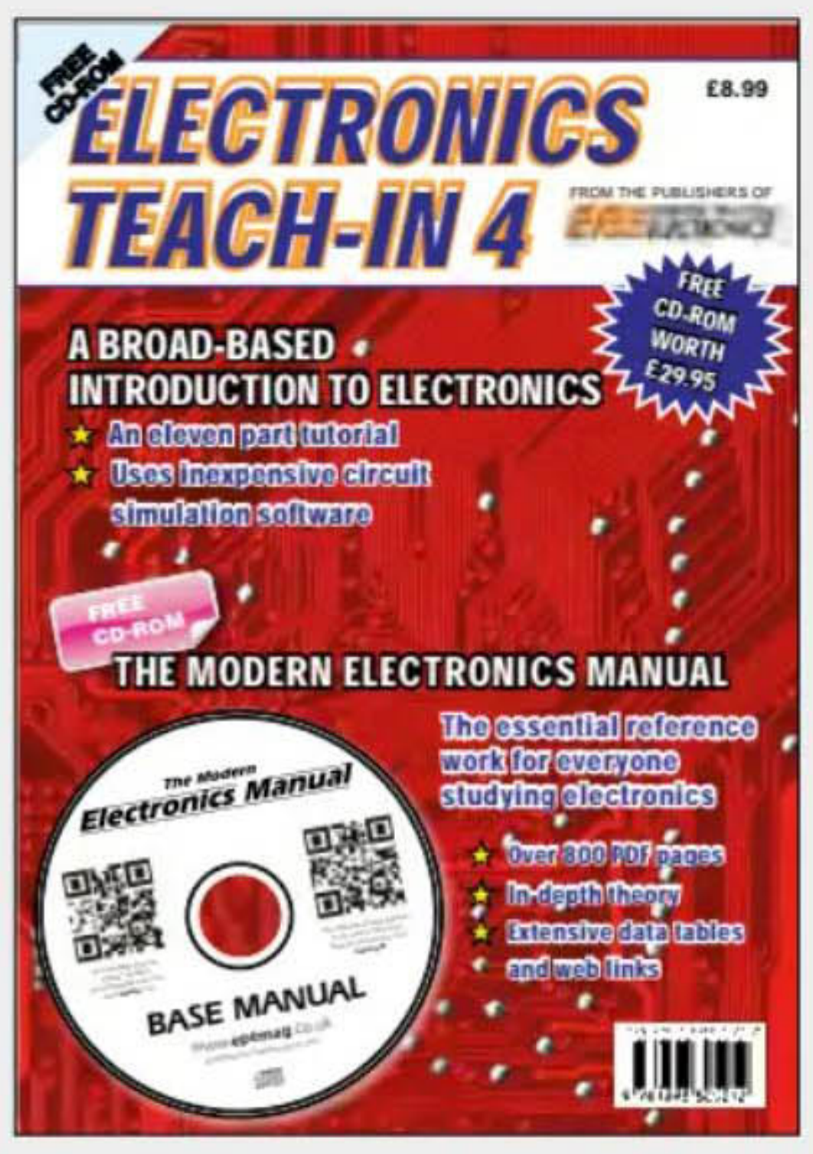

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Max's Cool Beans

By Max the Magnificent

Arduino Bootcamp – Part 18

O-M-Goodness gracious me. My head is buzzing with so many ideas that I don't know whether I'm coming or going. I have myriad topics I want to waffle about, but where to start waffling?

More power!

I've said it before, and I'll say it again – one of the great things about electronics is that there's always more than one way to do something. I've said it before, and I'll say it again (did someone just say that or is it déjà vu all over again?) – one of the pains with electronics is that there's usually so many ways of doing things that it can be hard to know what to do for the best. Sometimes your best bet is to flip a coin and allow fate to decide your course.

Over the course of this series, we've developed a way of powering our breadboards that involves using two light-emitting diodes (LEDs) to provide us with a high level of confidence that our power and ground rails are intact and working as expected.

I'm not going to rehash everything we've done in excruciating detail now (I'll save that for later). What I will do is say that you can remind yourself of our current setup by downloading an image of the latest and greatest incarnation of our dual breadboard platform (file **CB-Jun24-01.pdf**). As usual, all the files mentioned in this column are available from the June 2024 page of the *PE* website: **https://bit.ly/pe-downloads**

I've made mention of my friend Joe Farr on multiple occasions. Joe has a vast amount of practical knowledge. I learn something new whenever I chat with him. For example, while he was helping me debug the wiring issue we discussed in our previous column (*PE*, May 2024), Joe idly dropped into the conversation the fact that he usually powers his breadboards using a different scheme to the one we've adopted.

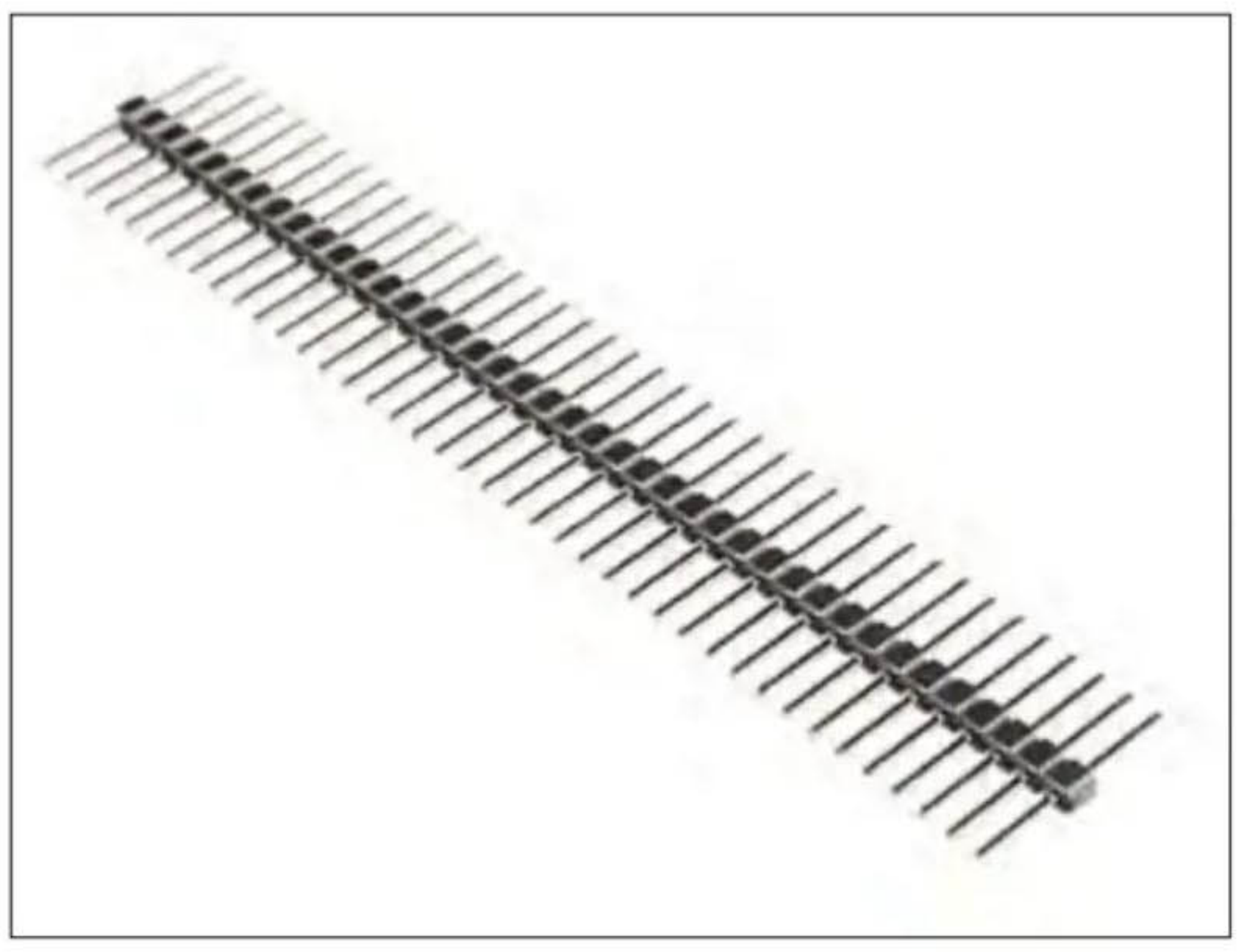


Fig.1. Long-tailed 0.1-inch pitch header pins.

We will look at this scheme in a moment, but – before we go there – Joe also mentioned that if he ever needs to perform some breadboard-related activity more than one time, he usually creates a breakout board (BOB) or something similar. He then makes a bunch of these and pops them in a drawer for later use.

Another trick Joe employs is to put a label on the front of the drawer saying what's inside. I'm reminded of the 'Brilliant!' adverts from Guinness – see: **https://bit.ly/3VDE0yt**

I'm sure you are muttering, 'That's obvious,' to yourself under your breath. Well, that's as maybe, but it's amazing how many of us – your humble narrator included – are convinced we will always remember where we put things, only to discover that we are deluding ourselves when the time comes.

In the case of any LEDs used to verify the presence of power on his breadboards, Joe mounts them and their associated current-limiting resistors on a pair of 0.1-inch-pitch header pins. You can purchase these pins in strips and then snip off the number you need. The ones we need here are long tailed on both sides (Fig.1). The conducting terminals are 6.25mm on each side with 2.5mm of plastic in the middle, so 15mm in all. You can find them all over the place, including Amazon, see: **https://bit.ly/3U1Vp2z**

Joe always associates the current-limiting resistor with the LED's anode terminal, thereby making it easy to remember what's what when plugging them into the power and ground rails. I've replicated Joe's scheme with the green and blue LEDs we've been using, along with their 680Ω (blue-grey-brown) current-limiting resistors (Fig.2).

Since we know all the experiments in this series are based on the 5V supplied by our Arduino Uno, we need do no more. In Joe's case, as his projects often include a mix of +12V and –12V for the analogue portions of his circuits, along with +5V and +3.3V for the digital sections, he uses different coloured LEDs (and different values of current-limiting resistors) for each voltage.

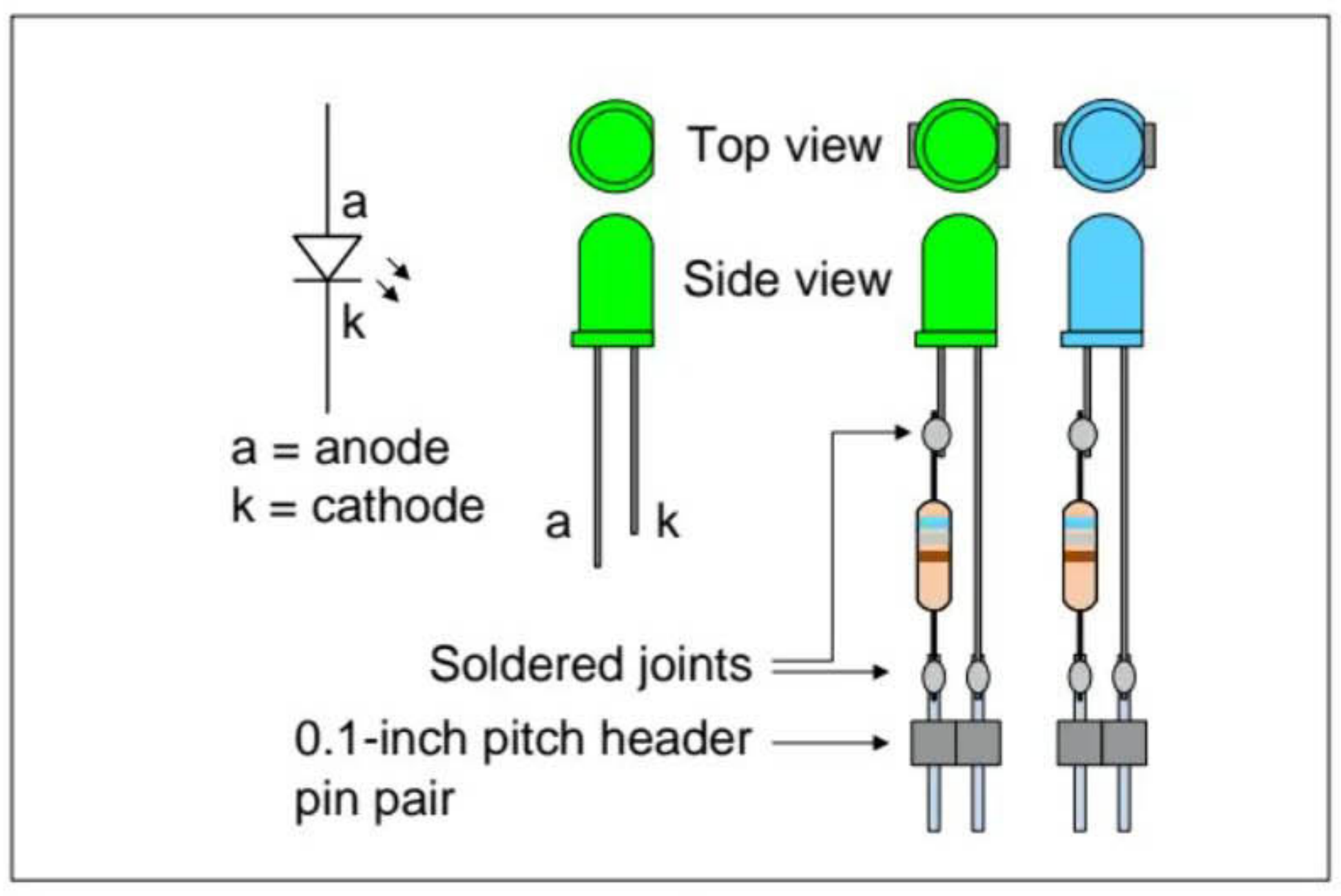
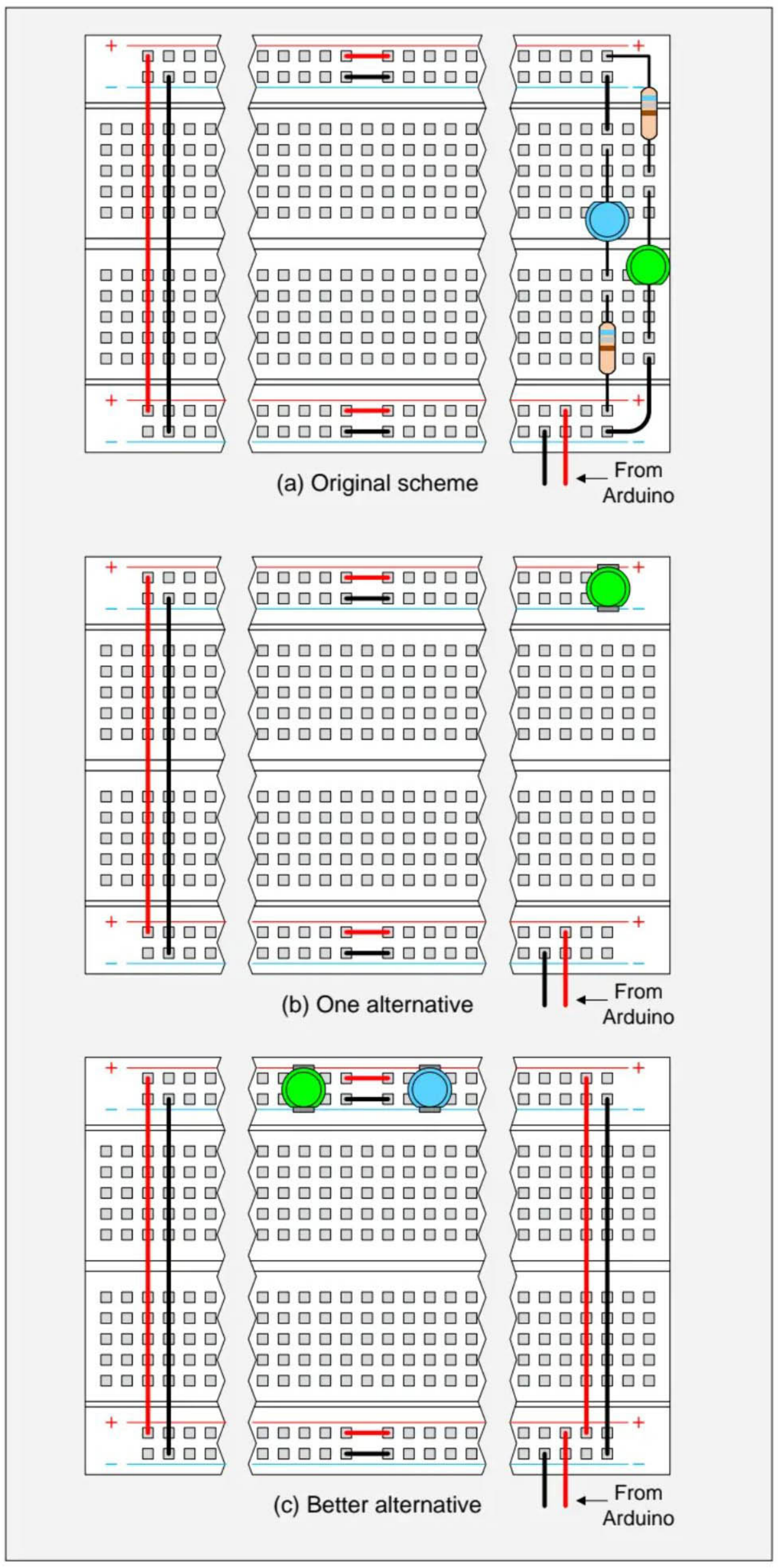


Fig.2. Constructing LED assemblies.

It's a bit ironic that – although we are working with solderless breadboards – we find ourselves needing to do a bit of soldering, but 'it's a funny old world and no mistake,' as they say (we talked about soldering, along with Alan Winstanley's handy-dandy *Basic Soldering Handbook*, in *PE*, March 2024).

Now let's turn our attention to our spiffy new power plan (Fig.3). Remember that I always prefer to have my breadboards oriented such that the red power rail is at the top (always doing things the same way helps cut down on errors involving mistakenly connecting things to the wrong rails). In all these examples, we're bringing 5V (red wire) and 0V (black wire) from the Arduino into the bottom right-hand corner of the breadboard. Also, we're including jumpers in the middle of the power and ground rails just in case we happen to find ourselves working with a split-rail board.

The way we've been doing things thus far is illustrated in Fig.3a. In this case, we link the bottom and top sets of power and ground rails using the red and black wires on the left-hand side of the board. By locating our green and blue LEDs on the right-hand side of the board, we verify that all the rails are intact. As I know from experience, it's very frustrating to spend time debugging a non-existent problem, only to discover that one's breadboard isn't fully powered up in the way one thinks it is.



(a) Original scheme

(b) One alternative

(c) Better alternative

Fig.3. Alternative power scenarios.

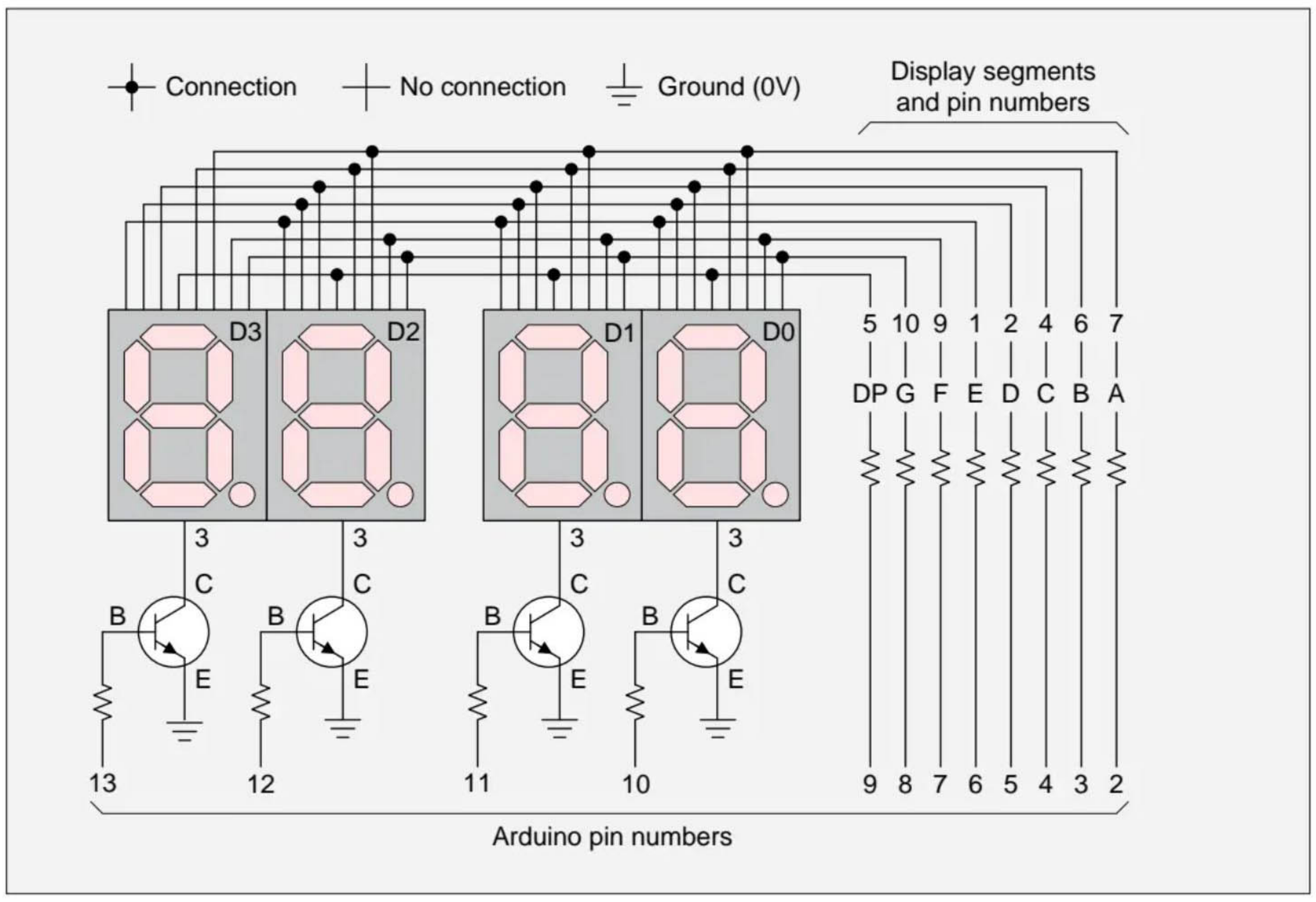


Fig.4. Upping our game to use four 7-segment displays.

Now that we have our snappy new LED assemblies from Fig.2, one possible scenario is to use one of these assemblies as illustrated in Fig.3b. By placing this single LED assembly in the upper right-hand corner of the board, we again verify that all the rails are intact.

A final alternative is to add additional red and black wires to link the bottom and top set of power and ground rails on the right-hand side of the board (Fig.3c). This redundancy provides increased reliability on the off chance that one of our wires becomes disconnected or one of our rails goes open circuit for some reason. We really require only one LED assembly, but I've used two (one either side of the jumpers in the middle of the upper rails) because… well, (a) they are different colours and (b) two LEDs are inherently more fun than one.

Of course, we don't have to change our existing setup now. This is just something for us to remember for future projects. Having said that, I've gone ahead and modified our master diagram anyway (file **CB-Jun24-02.pdf**).

I can't hold back!

In closing our previous column, I more than hinted that this month we were going to refresh our minds as to the concept of binary-coded decimal (BCD), after which we were to investigate various deployments of BCD-to-7-segment decoders in our clock prototype.

I'm afraid I fibbed. I hang my head in shame. I shall chastise myself soundly later. The problem is that I can't hold myself back any longer. When we were all a lot younger than we are today, we commenced our *Arduino Bootcamp* experiments using only a single 7-segment display. I'm sure that you, like me, look back on those halcyon days with fond nostalgia.

More recently (*PE*, May 2024), we upped our game to use a dual-display configuration, pushing ourselves to 'Boldly go,' as Captain James Tiberius Kirk might say.

And now? Well, as the eponymous character in *Dirk Gently's Holistic Detective Agency* once proclaimed: 'Let's think the unthinkable. Let's do the undoable. Let us prepare to grapple with the ineffable itself and see if we may not eff it after all.' Yes, you are correct, it's time for us to tentatively dip our toes into the quad-display waters.

From a hardware perspective, this is simply an extension of what we've done before. We already had two 7-segment displays that we called D0 and D1. We're going to add two more that we'll call D2 and D3 (Fig.4). Similarly, we were already using eight of the digital outputs (pins 2 through 9) on our Arduino Uno to drive eight 150Ω current-limiting resistors. The other sides of the resistors were connected to the anode (segment) terminals on displays D0 and D1, so we need to extend these wires to also drive displays D2 and D3. Finally, we need to add two more BC377 NPN transistors, along with 1kΩ current-limiting resistors on their base (B) control inputs and connect these to the Arduino, as shown in the schematic. Yes, of course, I've updated our master diagram to reflect this new setup (file **CB-Jun24-03.pdf**).

Super software

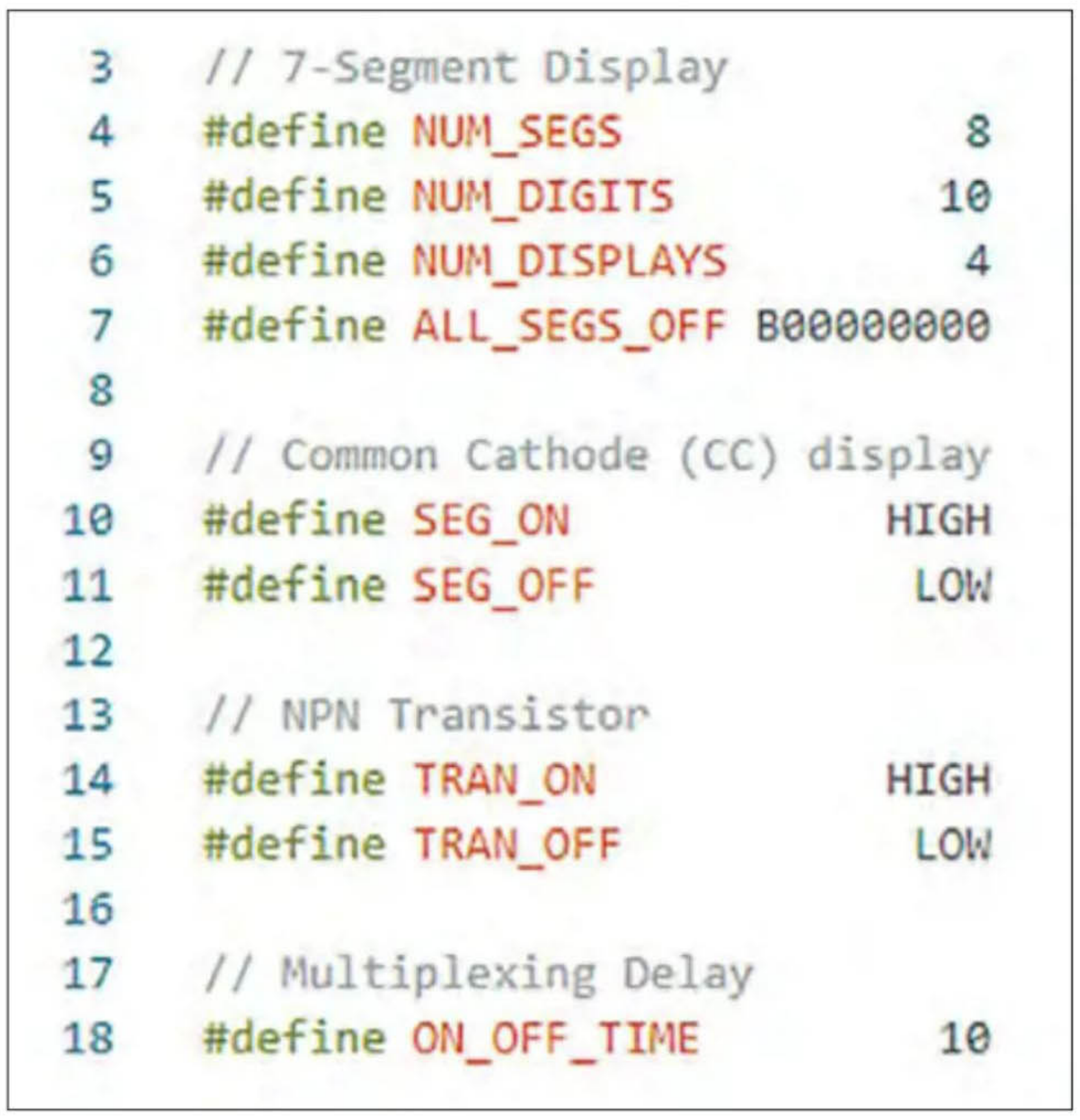
All we need now is some super software to drive our new setup. I just forked (copied) the final program from our previous column and made a few modifications. There's nothing we haven't seen before, but there are a few subtleties that will make it worth our while to peek at some of the bits and pieces.

As a reminder, we are multiplexing our four displays, which means only one will be active at a time. The main reason for doing this is that we currently have only enough pins on our Arduino to control one set of A, B, C, D, E, F, G, DP segments at a time. Also, we've selected our 150Ω current-limiting resistors to supply the maximum current (20mA) that the display segments are rated for. The Arduino's pins would be uncomfortable providing more than this amount of current for an extended period, so activating two or more displays simultaneously would be the opposite of a good idea.

In one respect, it's meaningless to think of our four displays in terms of 'least-significant' and 'most-significant' because we aren't using them to display a single numerical value *per se*. Having said this, for the purposes of our program, we're going to consider D0 and D3 as being the least- and most-significant, respectively.

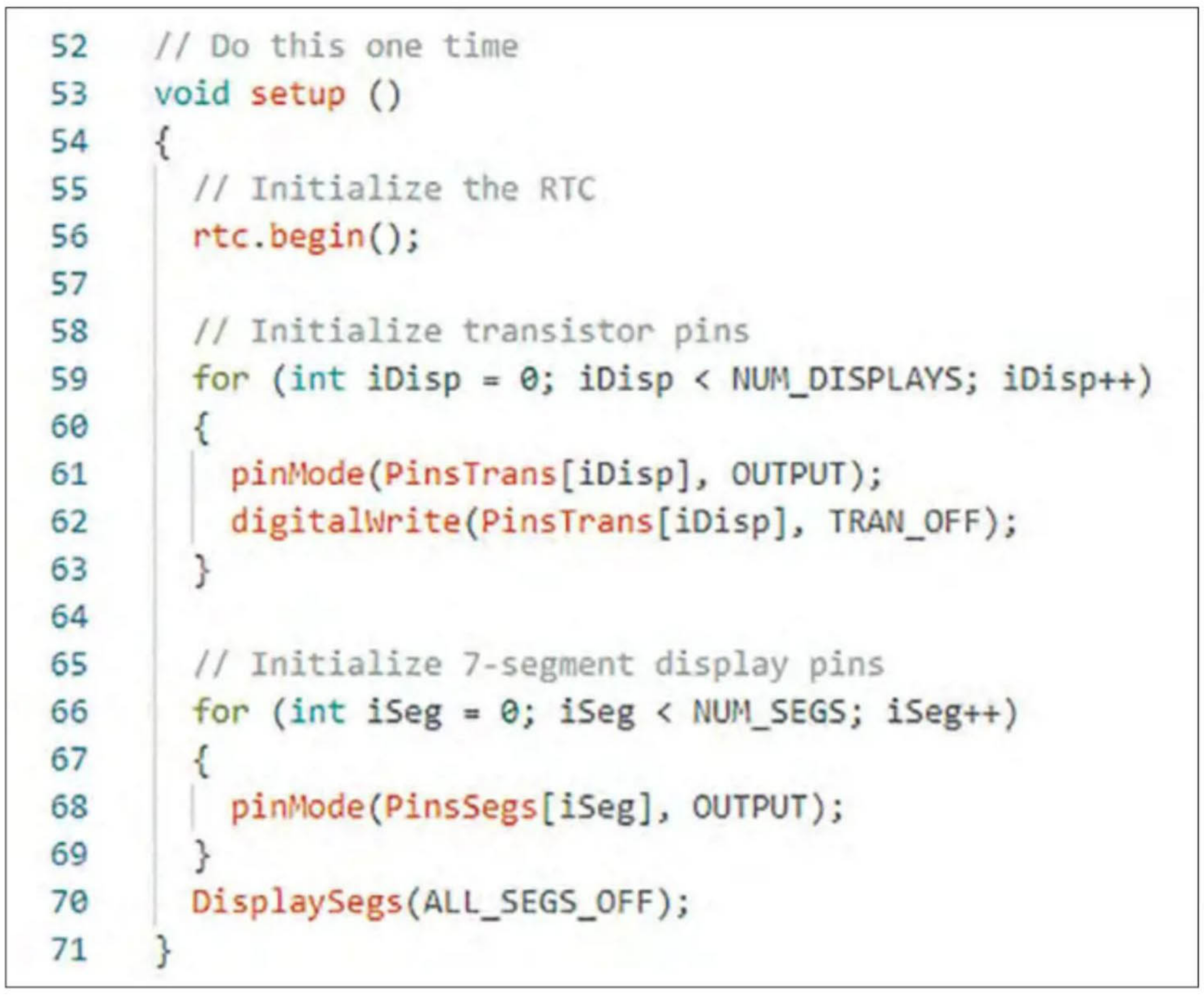
For reasons that will become apparent when we delve into the code, we are going to activate the displays in the order D0, D1, D2, and D3. Suppose, for example, we wish to display a time like 6:24. In our HH:MM format, we will include a leading 0 and present this as 06 24 (Fig.5).

OK, now let's look at our new program (file **CB-Jun24-04.txt**). We'll start with the definitions as shown in Listing 4a.



```
3   // 7-Segment Display
4   #define NUM_SEGS            8
5   #define NUM_DIGITS         10
6   #define NUM_DISPLAYS        4
7   #define ALL_SEGS_OFF B00000000
8
9   // Common Cathode (CC) display
10  #define SEG_ON           HIGH
11  #define SEG_OFF           LOW
12
13  // NPN Transistor
14  #define TRAN_ON          HIGH
15  #define TRAN_OFF          LOW
16
17  // Multiplexing Delay
18  #define ON_OFF_TIME        10
```

Listing 4a. Definitions.



```
52  // Do this one time
53  void setup ()
54  {
55    // Initialize the RTC
56    rtc.begin();
57
58    // Initialize transistor pins
59    for (int iDisp = 0; iDisp < NUM_DISPLAYS; iDisp++)
60    {
61      pinMode(PinsTrans[iDisp], OUTPUT);
62      digitalWrite(PinsTrans[iDisp], TRAN_OFF);
63    }
64
65    // Initialize 7-segment display pins
66    for (int iSeg = 0; iSeg < NUM_SEGS; iSeg++)
67    {
68      pinMode(PinsSegs[iSeg], OUTPUT);
69    }
70    DisplaySegs(ALL_SEGS_OFF);
71  }
```

Listing 4c. Our new `setup()` function.

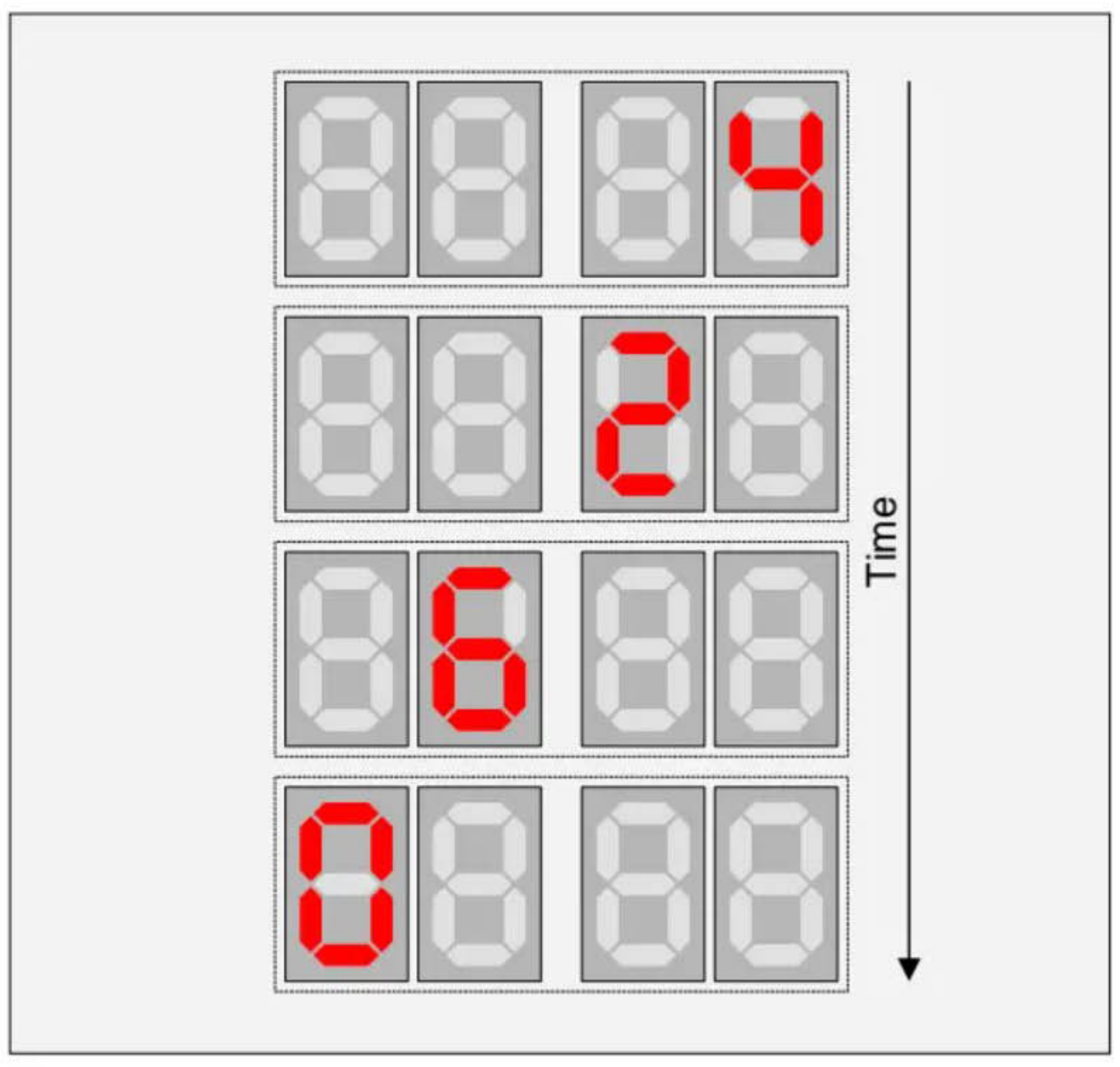
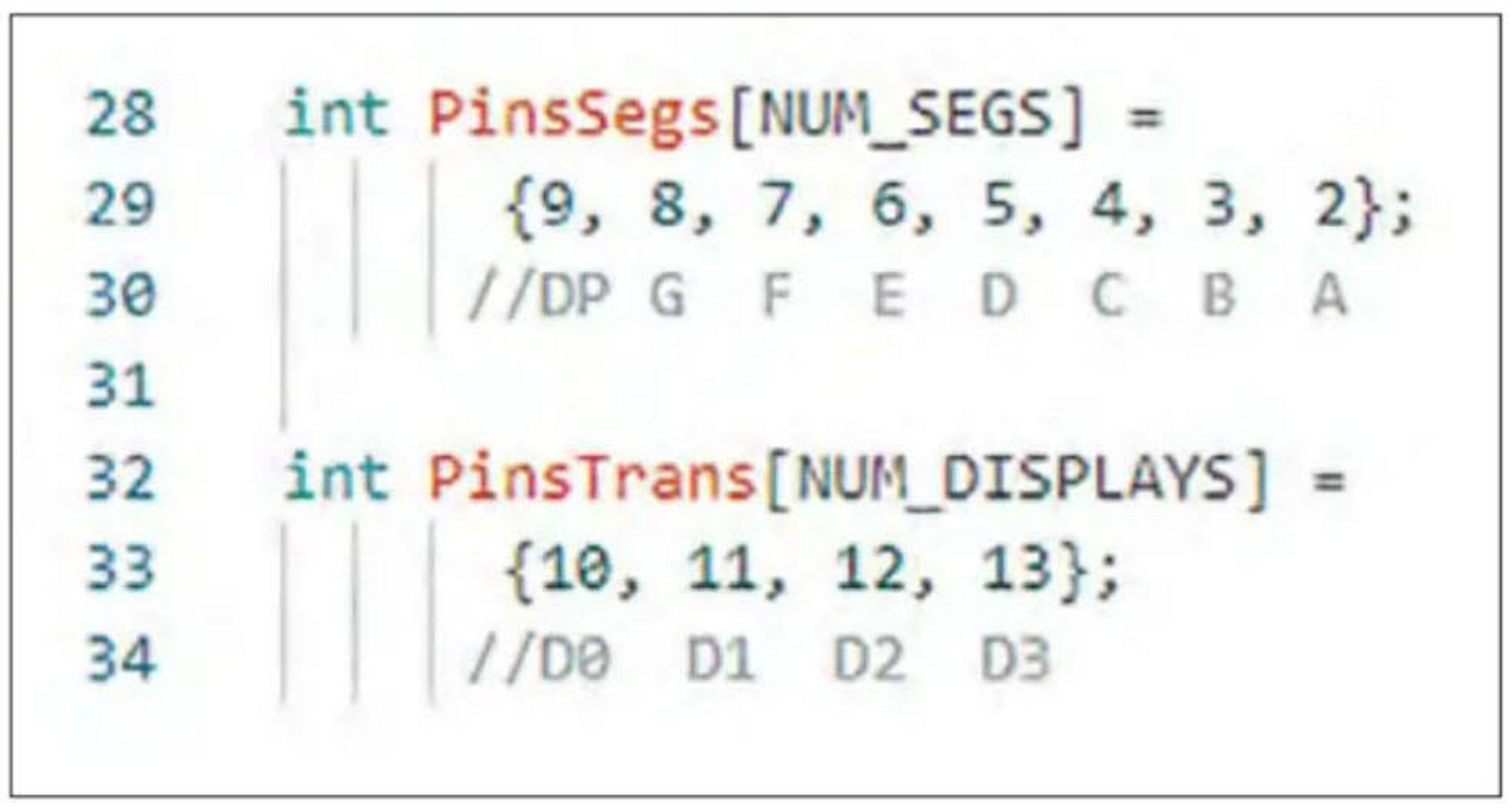


Fig.5. Order of display.

In addition to `NUM_SEGS` (the number of segments on each display) and `NUM_DIGITS` (the number of digits, 0 to 9, that we wish to display), we've added `NUM_DISPLAYS` (the number of displays, D0 to D3, we're now using).

Similarly, in addition to `SEG_ON` and `SEG_OFF`, to which we've assigned the `HIGH` and `LOW` values required to activate and deactivate the segments on our common-cathode displays, respectively, we've added `TRAN_ON` and `TRAN_OFF`, to which we've assigned the `HIGH` and `LOW` values required to activate and deactivate the NPN transistors we're using, respectively.

Next, let's turn our attention to our pin declarations and assignments (Listing 4b). In our previous column, there were several reasons why it made sense to declare the pins used to control the transistors individually. These reasons included our having only two displays, coupled with the way in which we decided to present values on these displays.



```
28  int PinsSegs[NUM_SEGS] =
29        {9, 8, 7, 6, 5, 4, 3, 2};
30       //DP G  F  E  D  C  B  A
31
32  int PinsTrans[NUM_DISPLAYS] =
33        {10, 11, 12, 13};
34       //D0  D1  D2  D3
```

Listing 4b. Pin assignments.

In our new program, In addition to the 8-element `PinsSegs[]` array, to which we've assigned the numbers of the pins used to drive the display segments, we've added a 4-element `PinsTrans[]` array, to which we've assigned the pins used to drive our transistors.

Remember that the elements in our `PinsTrans[]` array are numbered 0, 1, 2 and 3, which is the order in which we've assigned the pins used to drive the transistors associated with displays D0, D1, D2 and D3, respectively.

The `setup()` function is easy peasy lemon squeezy (Listing 4c). We start by initialising our real-time clock on Line 58. On Lines 66 to 69 we use a `for()` loop to define the pins driving our segments as being of type `OUTPUT`. Then, on Line 70, we call our `DisplaySegs()` function to turn all the segments off. We've seen this before in previous programs.

New to this program is the fact that, since we've now declared the pins controlling our transistors as an array, we can use another `for()` loop on Lines 59 to 63 to declare each pin as being of type `OUTPUT` and to then deactivate that transistor. The reason I inserted this before our original `for()` loop is to ensure all the transistors are turned off as soon as possible.

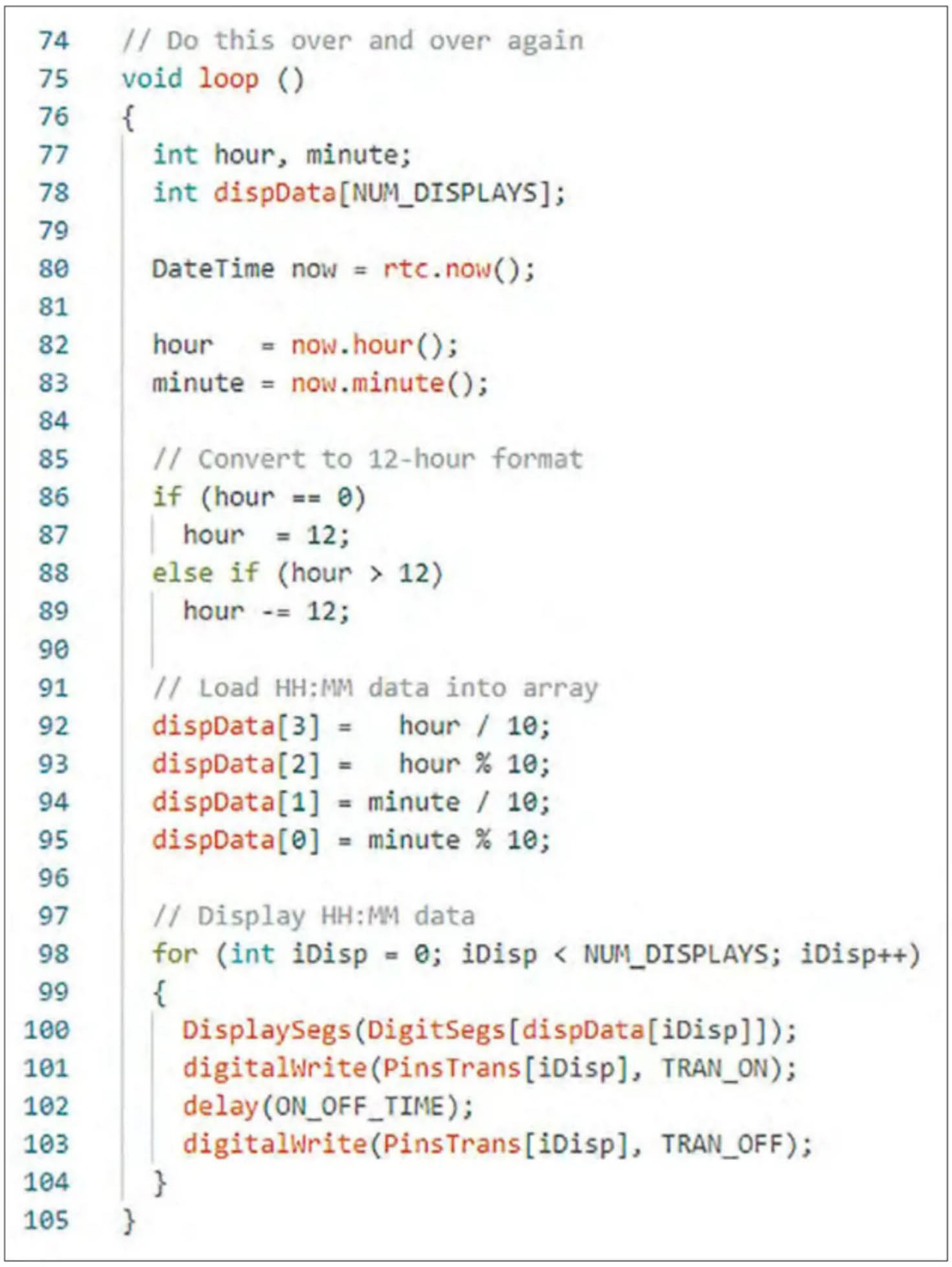
Finally, let's turn our attention to the `loop()` function (Listing 4d). After declaring the same `hour` and `minute` variables we've used before, on Line 78 we've added a new 4-element array called `dispData[]`. We are going to use this array to store the four 0 to 9 values we wish to present on our D0, D1, D2 and D3 displays.

We've seen the statements in Lines 80 to 89 in our previous program. However, on Lines 92 to 95, we now enter our HH:MM values into our `dispData[]` array. The combination of our `PinsTrans[]` and `dispData[]` arrays allows us to create the `for()` loop on Lines 98 to 104.

This loop cycles through the four displays in the order D0, D1, D2 and D3. Each time round the loop, on Line 100 we activate the segments we wish to display (we'll return to this in a moment), on Line 101 we activate the transistor associated with the current display, on Line 102 we wait for our `ON_OFF_TIME` delay, which is currently set to 10 (milliseconds), and on Line 103 we deactivate the transistor associated with the current display.

Line 100 might cause your brain to stumble a bit. The way to read this is like peeling an onion but the other way round. That is, we start with the deepest layer and work our way out. Thus, we start with our 'call' to `dispData[iData]`, which returns an integer containing the 0 to 9 value we wish to present on the current display. We then use this value in our 'call' to `DigitSegs[]`, which returns a byte containing the segment on/off values we need to use. We then pass this byte into the call to our trusty `DisplaySegs()` function.

Another way to think about this – and another way we could have implemented it – would be to break everything out into individual steps as follows:



```
// Do this over and over again
void loop ()
{
  int hour, minute;
  int dispData[NUM_DISPLAYS];

  DateTime now = rtc.now();

  hour   = now.hour();
  minute = now.minute();

  // Convert to 12-hour format
  if (hour == 0)
    hour  = 12;
  else if (hour > 12)
    hour -= 12;

  // Load HH:MM data into array
  dispData[3] =   hour / 10;
  dispData[2] =   hour % 10;
  dispData[1] = minute / 10;
  dispData[0] = minute % 10;

  // Display HH:MM data
  for (int iDisp = 0; iDisp < NUM_DISPLAYS; iDisp++)
  {
    DisplaySegs(DigitSegs[dispData[iDisp]]);
    digitalWrite(PinsTrans[iDisp], TRAN_ON);
    delay(ON_OFF_TIME);
    digitalWrite(PinsTrans[iDisp], TRAN_OFF);
  }
}
```

Listing 4d. Our new `loop()` function.

```
int tmpInt = dispData[iDisp];
byte tmpByte = DigitSegs[tmpInt]);
DisplaySegs(tmpByte);
```

This step-by-step approach is the way we would have done things earlier in this series because it can be easier for beginners to understand, but (a) we are beginners no more and (b) the approach we are now using is more concise. In fact, at some stage you may be surprised to discover yourself living in 'opposite world' where you find the step-by-step approach to be tedious and annoying, while the concise construct turns out to be easier on the eye and faster to parse and comprehend.

How does it look?

I'm glad you asked. It doesn't look very good. The digits are flickering horribly. Fortunately, I was expecting this to happen. Actually, I was hoping it would, thereby providing a 'teachable moment,' as it were.

At one stage in our previous column, we started to display the digits 4 and 2 on two displays. We defined `ON_OFF_TIME` as being 1000 (that's 1000 milliseconds (ms) or 1 second (s)). Then we looped around displaying the 4 on the first display for `ON_OFF_TIME` followed by the 2 on the second display for `ON_OFF_TIME`.

Next, we changed the value of `ON_OFF_TIME` to be 100 (that's 1/10 of a second). This allowed us to see both digits at the same time but with an annoying flicker. Finally, we changed `ON_OFF_TIME` to be 10 (that's 1/100 of a second), resulting in both digits being on with no discernable flicker.

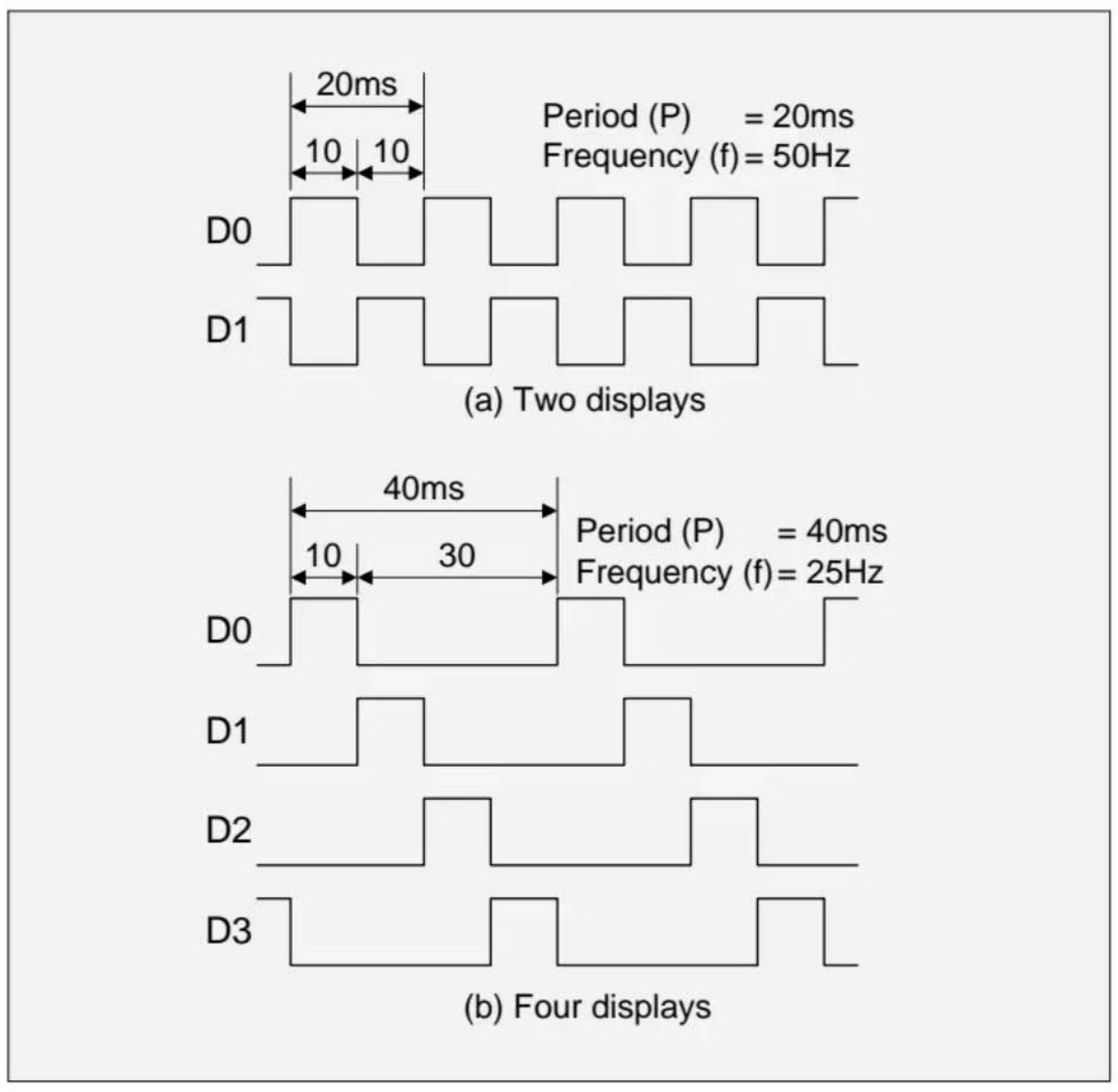


Fig.6. The origin of our flicker problem.

Since each display is on for 10ms and off for 10ms, this means each has a repeating cycle time, or period (*P*), of 20ms. In turn, this means each display is turning on and off with a frequency (*f*), which is 1/*P*. Remembering that frequency is specified in hertz (Hz), which is the number of cycles per second, then our frequency = 1000/20 = 50Hz (Fig.6a).

The problem is that we are still using the same `ON_OFF_TIME` value of 10 in our new program (Line 18 in Listing 4a). Now that we are using four displays, this means each display is on for 10ms and off for 30ms. In turn, this means each display has a period of 40ms and a frequency of 25Hz. Hence the flicker (Fig.6b).

First, I tried changing `ON_OFF_TIME` to 5, thereby returning us to having a flicker-free frequency of 50Hz. Eventually, however, I decided to use an `ON_OFF_TIME` value of 2, resulting in each display having a period of 8ms and a frequency of 125Hz.

The current situation is very tasty (Fig.7). Of course, since each display is now on for only 25% of the time, it's only a quarter as bright as a full-on display. However, this would really become apparent only if we had a full-on display for comparison. As we discussed in last month's column, the human eye has a wide dynamic range coupled with a non-linear response to brightness. The result is that our four displays still appear to be reasonably bright. Even better, in a future column, we will discuss an alternative approach to boost our brightness.

Online resources

For the purposes of this series, I'm going to assume that you are already familiar with fundamental concepts like voltage, current and resistance. If not, you might want to start by perusing and pondering a short series of articles I penned on these very topics – see: **https://bit.ly/3EguiJh**

Similarly, I'll assume you are no stranger to solderless breadboards. Having said this, even if you've used these little scamps before, there are some aspects to them that can trap the unwary, so may I suggest you feast your orbs on a column I wrote just for you – see: **https://bit.ly/3NZ70uF**

Last, but not least, you will find a treasure trove of resources at the **Arduino.cc** website, including example programs and reference documentation.

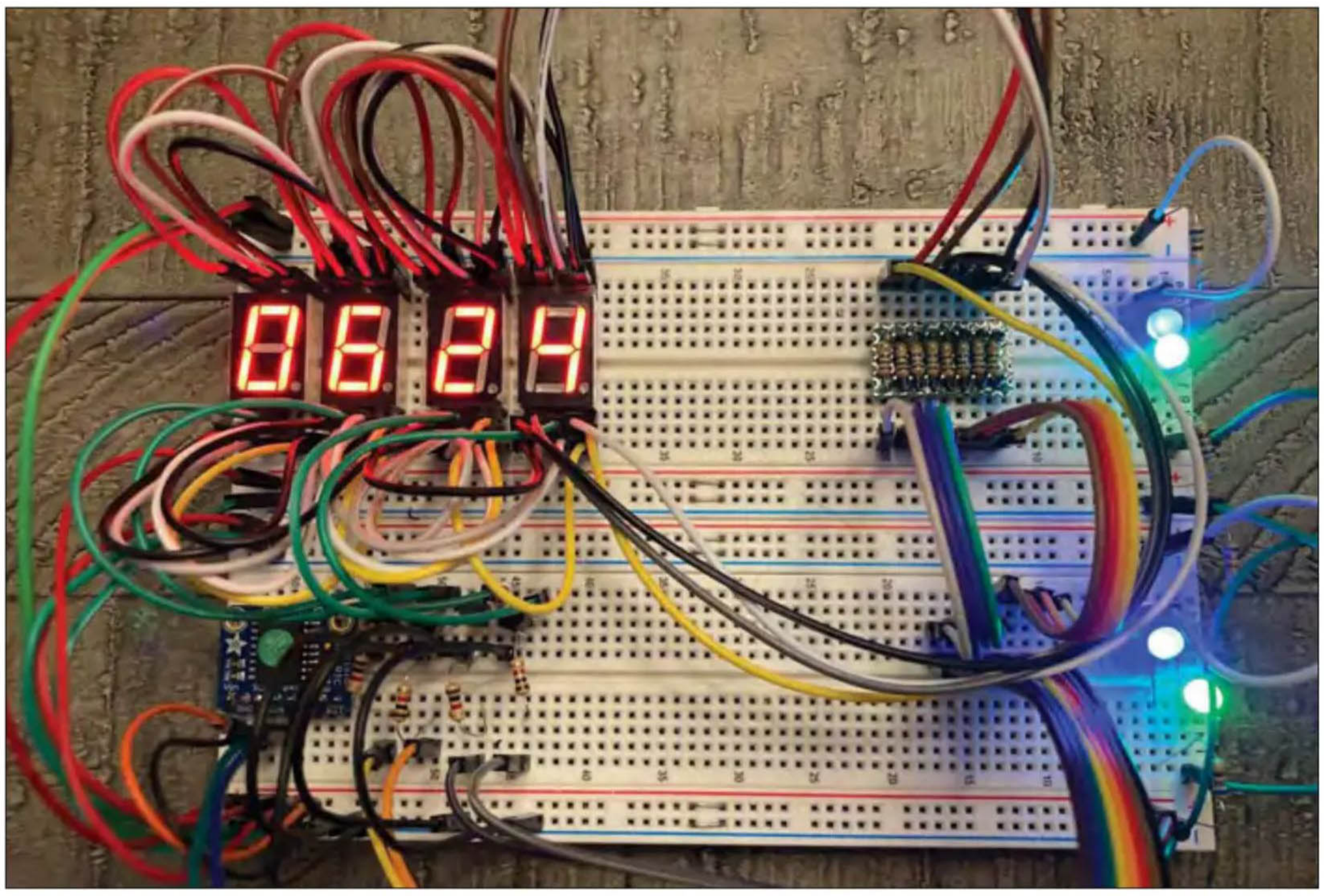


Fig.7. It's alive! It's alive!

You are thinking out loud again. I can almost hear you muttering, 'What's that little board in the upper right-hand corner where our eight 150Ω current-limiting resistors used to be?' I have to say I'm impressed that you spotted that. All will be revealed in next month's column. Meanwhile…

Just one more thing…

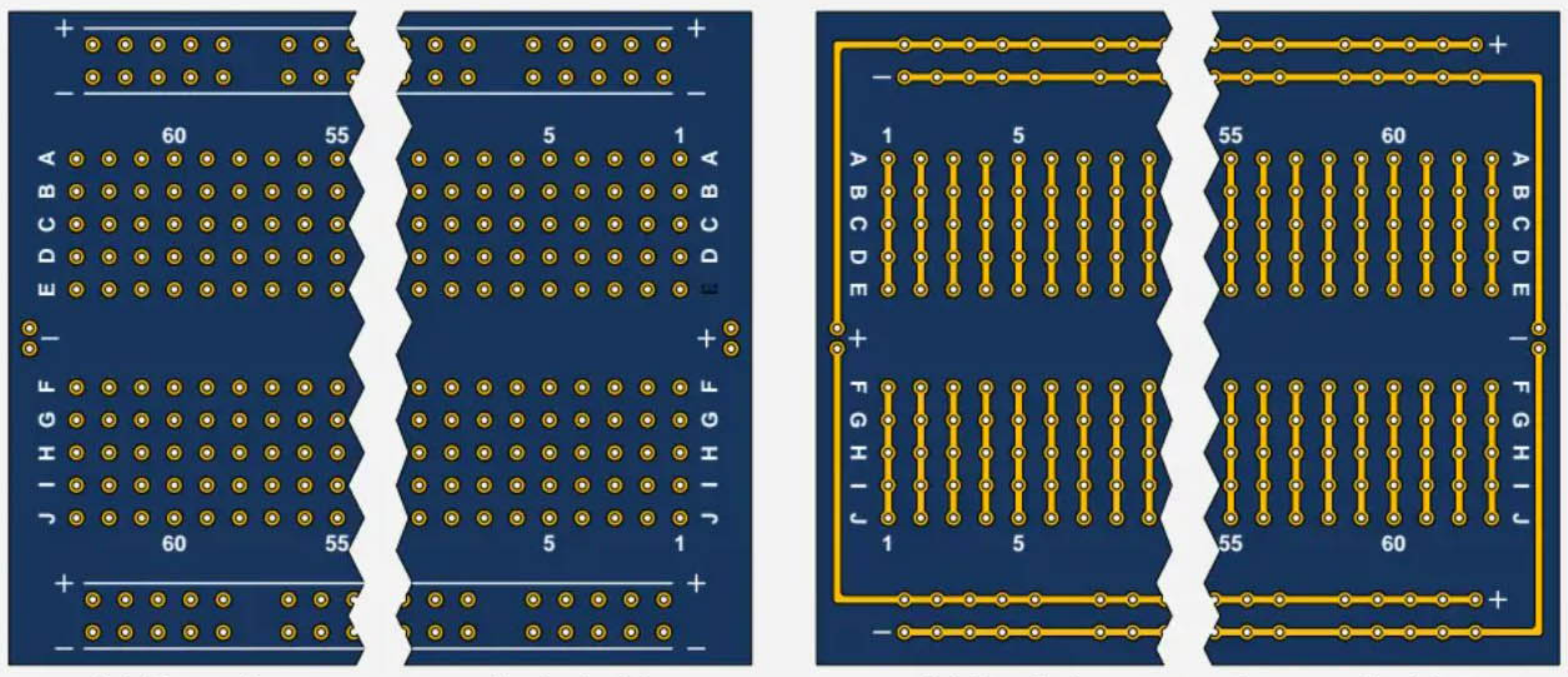
We still have more to do, but once we've finally finished evolving and experimenting with our prototype clock, we may wish to create a more permanent and robust implementation. One option is to use a free schematic capture and layout program to design our own custom printed circuit board (PCB) and then have it fabricated somewhere. There are lots of tools and fabs out there, but that's a whole different ballgame. (This could be a topic for one or more *Cool Beans* columns in the future. If you would be interested in something like this, please email me to let me know.)

An alternative approach is to replicate our final design in a more robust and comelier manner. With respect to the 'more robust' part, we could purchase some *solderable* breadboards with the look-and-feel of our *solderless* breadboards. There are various vendors of these boards, each offering their own interpretation, but the main terminal holes and power rails are typically to be found in the expected locations (Fig.8).

Observe the way in which the power and ground rails are split at the left- and right-hand sides on the back side of the board. This allows us to use multiple power supplies (eg, 5V and 3.3V) and/or multiple grounds (eg, separate analogue and digital grounds) if so required. Alternatively, these can be connected using jumper wires.

One example is the large single universal solderable breadboard from Treedix (**https://bit.ly/3Tsn38t**). But what about something like our clock project, which currently employs two breadboards? Fear not, because the guys and gals at Treedix have us covered with their large dual universal solderable breadboard – see: **https://bit.ly/3IuHYl6**

What about the wiring? Thus far, we've been using multicore jumper wires to make our connections. However, as we see in Fig.7, this isn't an approach we would wish to use on something we wanted to display



(a) Front (component and wire) side

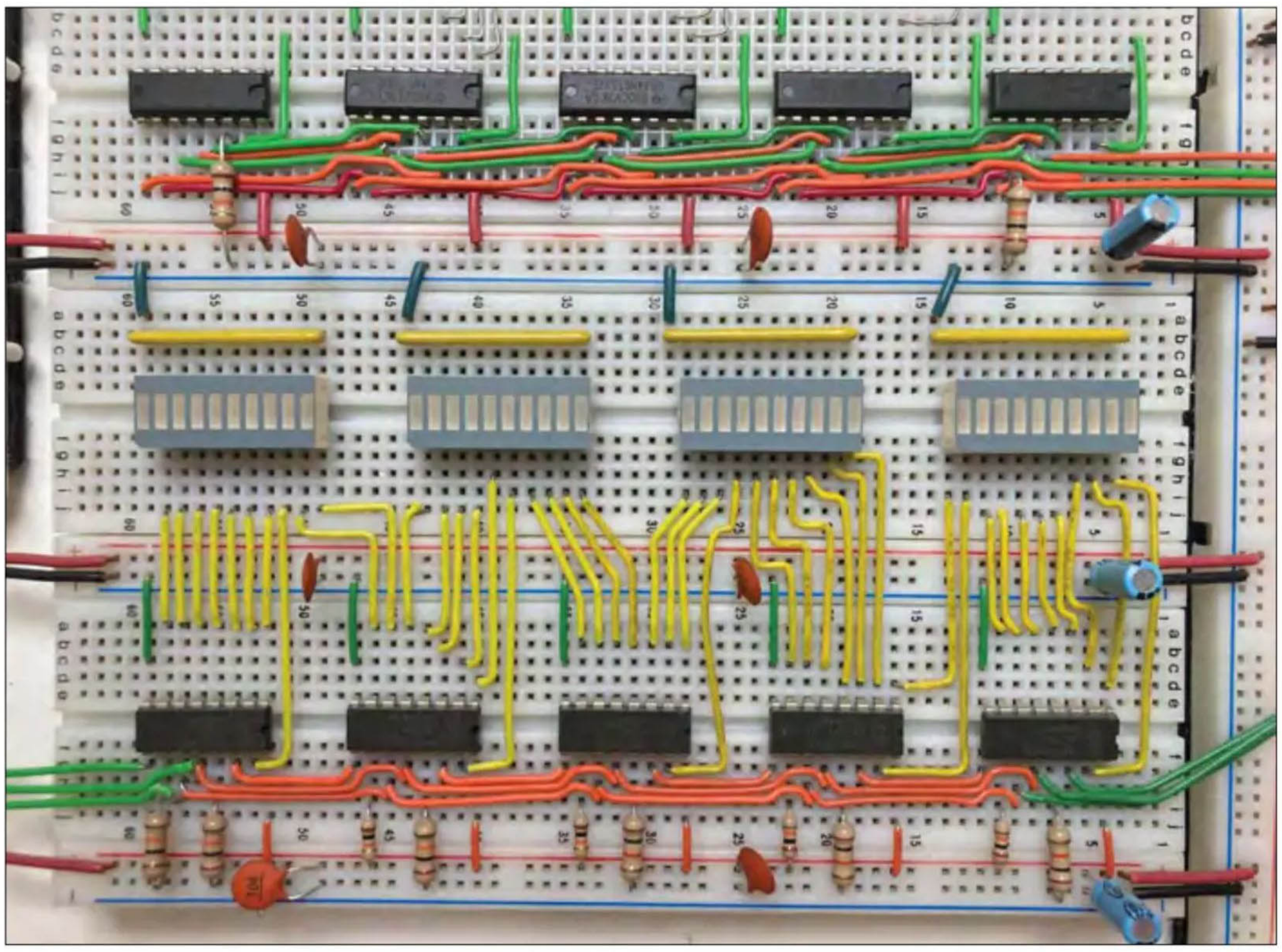
(b) Back (power and ground) side

Fig.8. Generic example of a solderable breadboard.

Fig.9. Kit of pre-stripped, pre-formed, solid core jumper wires.

Components from Part 1	
LEDs (assorted colours)	https://amzn.to/3E7VAQE
Resistors (assorted values)	https://amzn.to/3O4RvBt
Solderless breadboard	https://amzn.to/3O2L3e8
Multicore jumper wires (male-male)	https://amzn.to/3O4hnxk
Components from Part 2	
7-segment display(s)	https://amzn.to/3Afm8yu
Components from Part 5	
Momentary pushbutton switches	https://amzn.to/3Tk7Q87
Components from Part 6	
Passive piezoelectric buzzer	https://amzn.to/3KmxjcX
Components for Part 9	
SW-18010P vibration switch	https://bit.ly/46SfDA4
Components for Part 10	
Breadboard mounting trimpots	https://bit.ly/3QAuz04
Components for Part 12	
Light-Dependent Resistor	https://bit.ly/3S2430m
Components for Part 13	
BC337 NPN Transistor	https://bit.ly/40xAgyS
Components for Part 14	
HC-SR04 Ultrasonic Sensor	https://bit.ly/49AMBq4
Components for Part 15	
Real-Time Clock (RTC)	https://bit.ly/3S9OjHl
Components for Part 18	
Long tailed (0.1-inch pitch) header pins	https://bit.ly/3U1Vp2z

Fig.10. An example of an old project using solid core jumper wires.



to family and friends. One approach is to splash the cash for a kit of pre-stripped, pre-formed, solid core jumper wires (Fig.9). You can find these on Amazon – see: **https://bit.ly/3vDs2KK**

A lot of the time you'll need to cut them down and bend them around a bit, but the result can be quite pleasing to the eye. For example, consider a portion of one of my old projects from yesteryear (Fig.10).

Next time…

On the bright side, our existing clock works like a charm. On the downside, we've used all 12 of our digital pins – eight to control the display segments and four to control the transistors (we aren't touching pins 0 and 1 because these are used by the Arduino to communicate with our host computer). This means we have no pins spare to add additional functionality (sad face).

But turn that frown upside down into a smile because we have some cunning tricks up our sleeves (watch carefully – at no time will my hands leave the ends of my arms). In our next column, we really and truly are going to refresh our minds as to the concept of binary-coded decimal (BCD) and then investigate various deployments of BCD-to-7-segment decoders in our clock (otherwise my name's not **Max the Magnificent**). Until next time, have a good one!

Cool bean Max Maxfield (Hawaiian shirt, on the right) is emperor of all he surveys at **CliveMaxfield.com** – the go-to site for the latest and greatest in technological geekdom.

Comments or questions? Email Max at: **max@CliveMaxfield.com**

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HP 54600B Oscilloscope Analogue/Digital Dual Trace 100MHz Only £75, with accessories £125

LAMBDA GENESYS	PSU GEN100-15 100V 15A Boxed As New	£400
LAMBDA GENESYS	PSU GEN50-30 50V 30A	£400
IFR 2025	Signal Generator 9kHz – 2.51GHz Opt 04/11	£900
IFR 2948B	Communication Service Monitor Opts 03/25 Avionics	POA
IFR 6843	Microwave Systems Analyser 10MHz – 20GHz	POA
R&S APN62	Syn Function Generator 1Hz – 260kHz	£295
Agilent 8712ET	RF Network Analyser 300kHz – 1300MHz	POA
HP8903A/B	Audio Analyser	£750 – £950
HP8757D	Scaler Network Analyser	POA
HP3325A	Synthesised Function Generator	£195
HP3561A	Dynamic Signal Analyser	£650
HP6032A	PSU 0-60V 0-50A 1000W	£750
HP6622A	PSU 0-20V 4A Twice or 0-50V 2A Twice	£350
HP6624A	PSU 4 Outputs	£400
HP6632B	PSU 0-20V 0-5A	£195
HP6644A	PSU 0-60V 3.5A	£400
HP6654A	PSU 0-60V 0-9A	£500
HP8341A	Synthesised Sweep Generator 10MHz – 20GHz	£2,000
HP83630A	Synthesised Sweeper 10MHz – 26.5 GHz	POA
HP83624A	Synthesised Sweeper 2 – 20GHz	POA
HP8484A	Power Sensor 0.01-18GHz 3nW-10µW	£75
HP8560E	Spectrum Analyser Synthesised 30Hz – 2.9GHz	£1,750
HP8563A	Spectrum Analyser Synthesised 9kHz – 22GHz	£2,250
HP8566B	Spectrum Analsyer 100Hz – 22GHz	£1,200
HP8662A	RF Generator 10kHz – 1280MHz	£750
Marconi 2022E	Synthesised AM/FM Signal Generator 10kHz – 1.01GHz	£325
Marconi 2024	Synthesised Signal Generator 9kHz – 2.4GHz	£800
Marconi 2030	Synthesised Signal Generator 10kHz – 1.35GHz	£750
Marconi 2023A	Signal Generator 9kHz – 1.2GHz	£700

Marconi 2305	Modulation Meter	£250
Marconi 2440	Counter 20GHz	£295
Marconi 2945/A/B	Communications Test Set Various Options	POA
Marconi 2955	Radio Communications Test Set	£595
Marconi 2955A	Radio Communications Test Set	£725
Marconi 2955B	Radio Communications Test Set	£800
Marconi 6200	Microwave Test Set	£1,500
Marconi 6200A	Microwave Test Set 10MHz – 20GHz	£1,950
Marconi 6200B	Microwave Test Set	£2,300
Marconi 6960B	Power Meter with 6910 sensor	£295
Tektronix TDS3052B	Oscilloscope 500MHz 2.5GS/s	£1,250
Tektronix TDS3032	Oscilloscope 300MHz 2.5GS/s	£995
Tektronix TDS3012	Oscilloscope 2 Channel 100MHz 1.25GS/s	£450
Tektronix 2430A	Oscilloscope Dual Trace 150MHz 100MS/s	£350
Tektronix 2465B	Oscilloscope 4 Channel 400MHz	£600
Farnell AP60/50	PSU 0-60V 0-50A 1kW Switch Mode	£300
Farnell XA35/2T	PSU 0-35V 0-2A Twice Digital	£75
Farnell AP100-90	Power Supply 100V 90A	£900
Farnell LF1	Sine/Sq Oscillator 10Hz – 1MHz	£45
Racal 1991	Counter/Timer 160MHz 9 Digit	£150
Racal 2101	Counter 20GHz LED	£295
Racal 9300	True RMS Millivoltmeter 5Hz – 20MHz etc	£45
Racal 9300B	As 9300	£75
Solartron 7150/PLUS	6½ Digit DMM True RMS IEEE	£65/£75
Solatron 1253	Gain Phase Analyser 1mHz – 20kHz	£600
Solartron SI 1255	HF Frequency Response Analyser	POA
Tasakago TM035-2	PSU 0-35V 0-2A 2 Meters	£30
Thurlby PL320QMD	PSU 0-30V 0-2A Twice	£160 – £200
Thurlby TG210	Function Generator 0.002-2MHz TTL etc Kenwood Badged	£65

HP/Agilent HP 34401A Digital Multimeter 6½ Digit £325 – £375

HP33120A	Function Generator 100 microHz – 15MHz	£350
HP53131A	Universal Counter 3GHz Boxed unused	£600
HP53131A	Universal Counter 225MHz	£350
Audio Precision	SYS2712 Audio Analyser – in original box	POA
Datron 4708	Autocal Multifunction Standard	POA
Druck DPI 515	Pressure Calibrator/Controller	£400
Datron 1081	Autocal Standards Multimeter	POA
ENI 325LA	RF Power Amplifier 250kHz – 150MHz 25W 50dB	POA
Keithley 228	Voltage/Current Source	POA
Time 9818	DC Current & Voltage Calibrator	POA

Marconi 2955B Radio Communications Test Set – £800

AUDIO OUT

By Jake Rothman

Switching in audio equipment – Part 1

Switching is the most basic function in electronics, beginning with the old-fashioned knife switch (Fig.1) from which the circuit symbol is derived today. However, audio systems require specialised switching of very small signals, with no added noise, clicks or distortion. There are also psychological aspects to audio switching, such as how the mechanical aspect of the switch feels to the user. Mechanical noise is also very important; a switch that emitted a loud mechanical clunk, for example, would not be acceptable in a recording environment.

There is also the whole area of ergonomics or the science of control-surface design to consider. Well-designed switch positioning is vital to avoid mistakes in operation, such as the output of a radio station inadvertently being turned off. In addition to this, music technology and Hi-Fi equipment also has to satisfy the artistic needs of creative people. (In my experience these people seem to have what I call a wider 'dynamic arm envelope' – they are are much more likely to accidentality knock switches! Usually, at the worst possible time.)

Power switching.

Even mains power switching has an aspect that is almost unique to audio. The switch position is often down for 'on', as shown in Fig.2. This is in contrast to most other electronic equipment (such as a bench power supply) which you wouldn't want to turn on accidentally; it is 'up' for on. It doesn't stop there; audio mains wiring from the input power socket to the front panel switch mustn't emit hum into the sensitive circuitry. Some Hi-Fi designers obviate this by putting the mains wiring and switch at the back and use a mechanical rod to couple the front panel button (Fig.3). This is difficult for home and small batch construction since custom mouldings and specialist mechanical items are needed. There is also the travesty of rear-mounted mains switches, great (not!) when the unit is mounted in a rack against a wall.

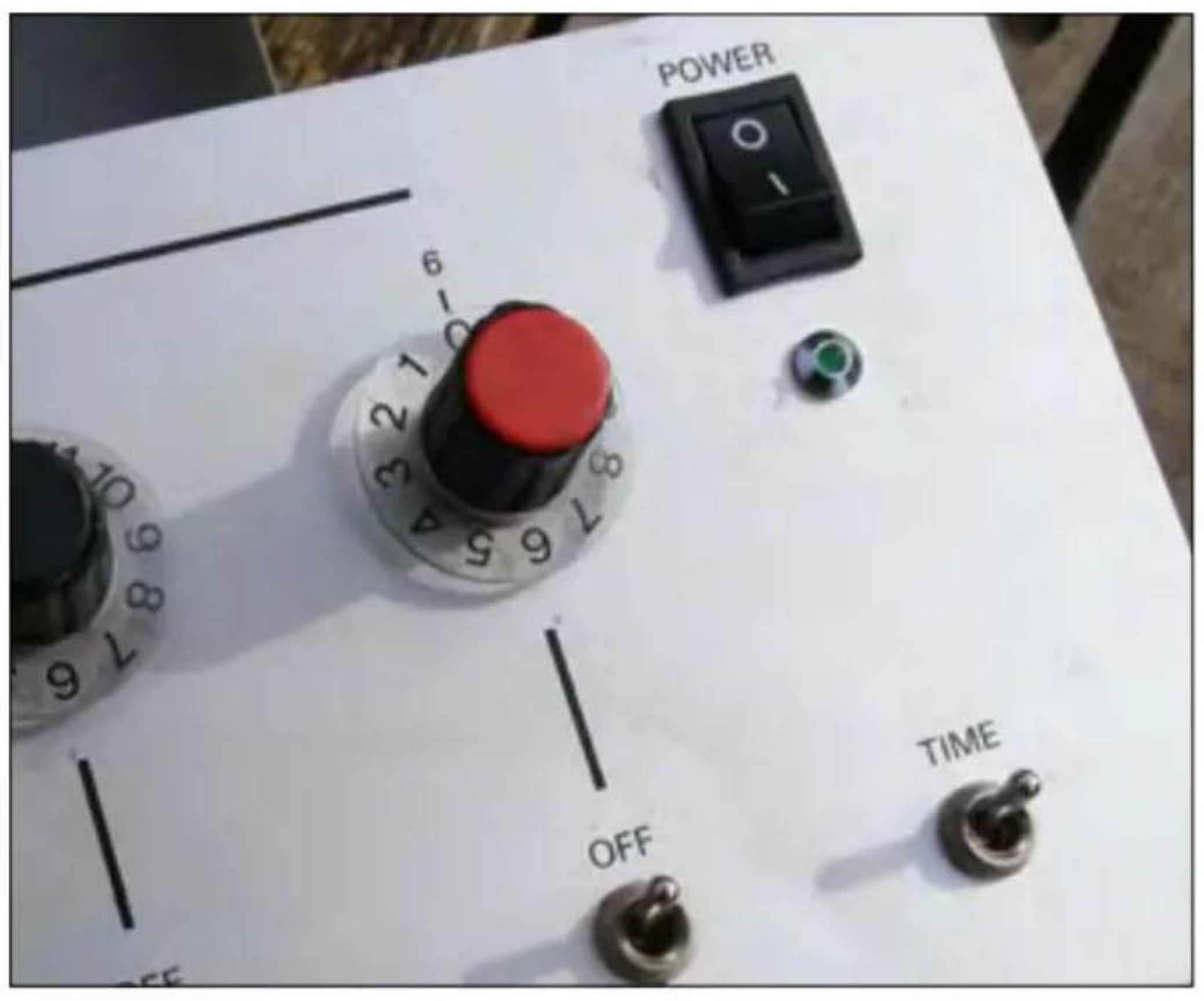


Fig.2. In audio it's considered 'much worse' if a switch gets knocked to off, so I prefer a switch orientation such that down is always on.

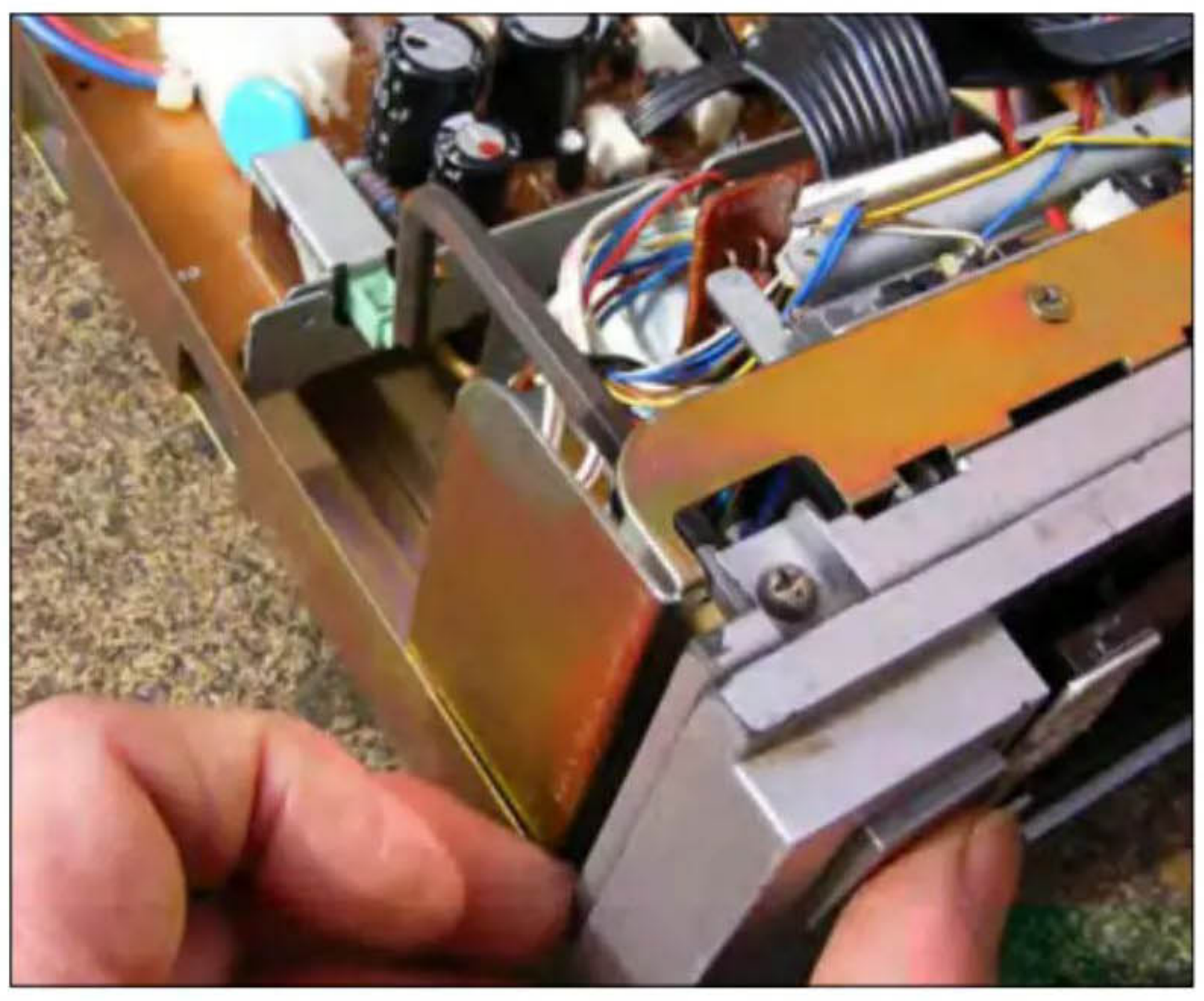


Fig.3. This old cassette deck has the mains switch actuated by a mechanical rod to keep it away from the sensitive playback head.

I always front mount the mains switch and have always used it to switch both the live and the neutral – which nowadays is a mandated safety requirement. This needs a double pole (DP) switch, such as the rocker switch shown in Fig.4. The two pairs of wires going to and from the switch need to be twisted tightly and moved away from sensitive circuit areas to reduce magnetic emissions. These wires should also be run along the corner of the metal box for partial electrostatic screening. In Orfoton moving-coil pick-up pre-amplifiers, the mains wiring is enclosed in a copper tube for screening. I've used this idea, employing short lengths of micro-bore central heating pipe. In low-cost equipment, hum (and

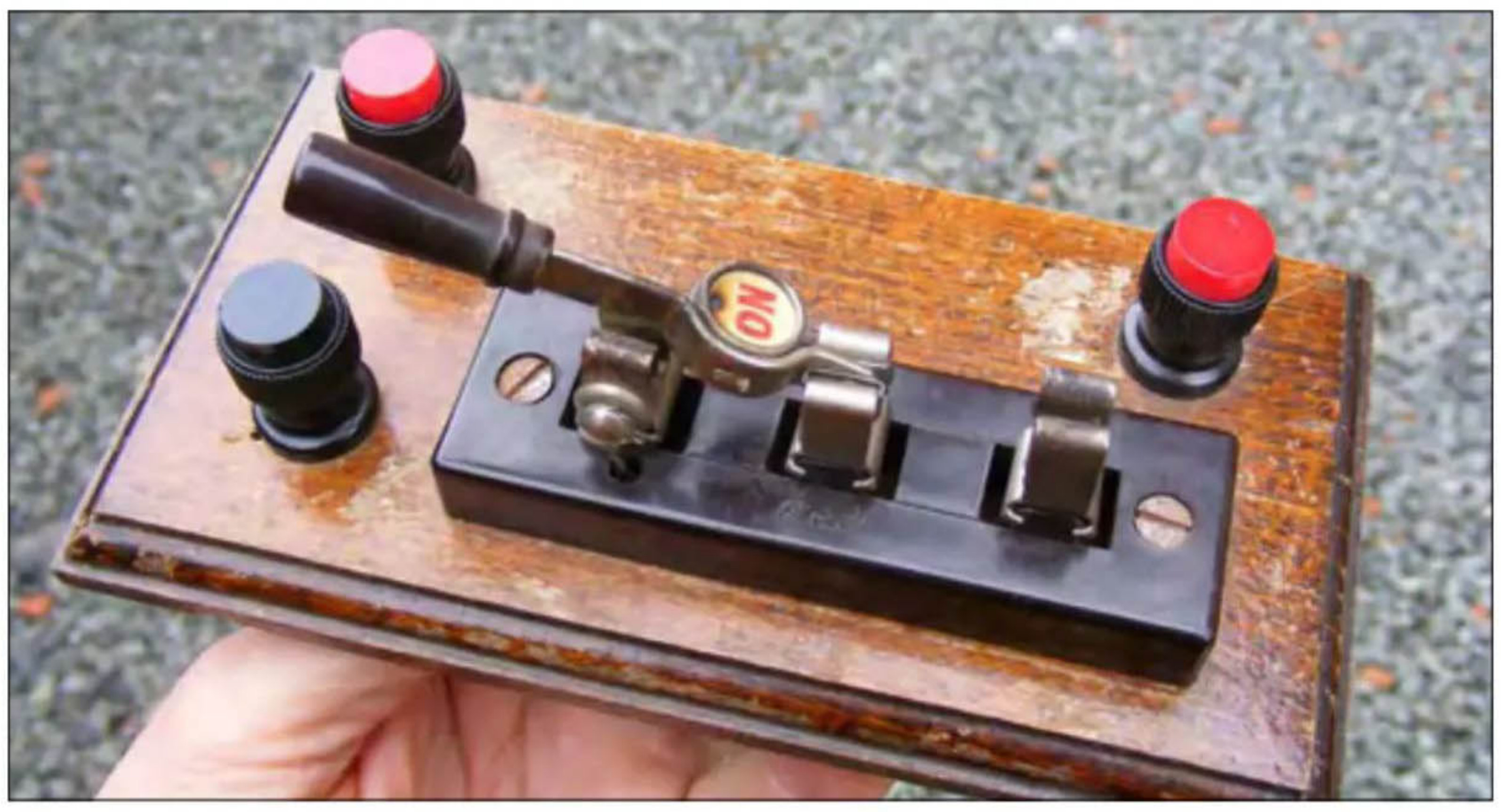


Fig.1. It's horror movie time. The old-fashioned knife switch would today be called a 'wiping contact single-pole double-throw (SPDT) switch' and would be considered irredeemably 'non-compliant' by any health and safety inspector; and they'd be right!

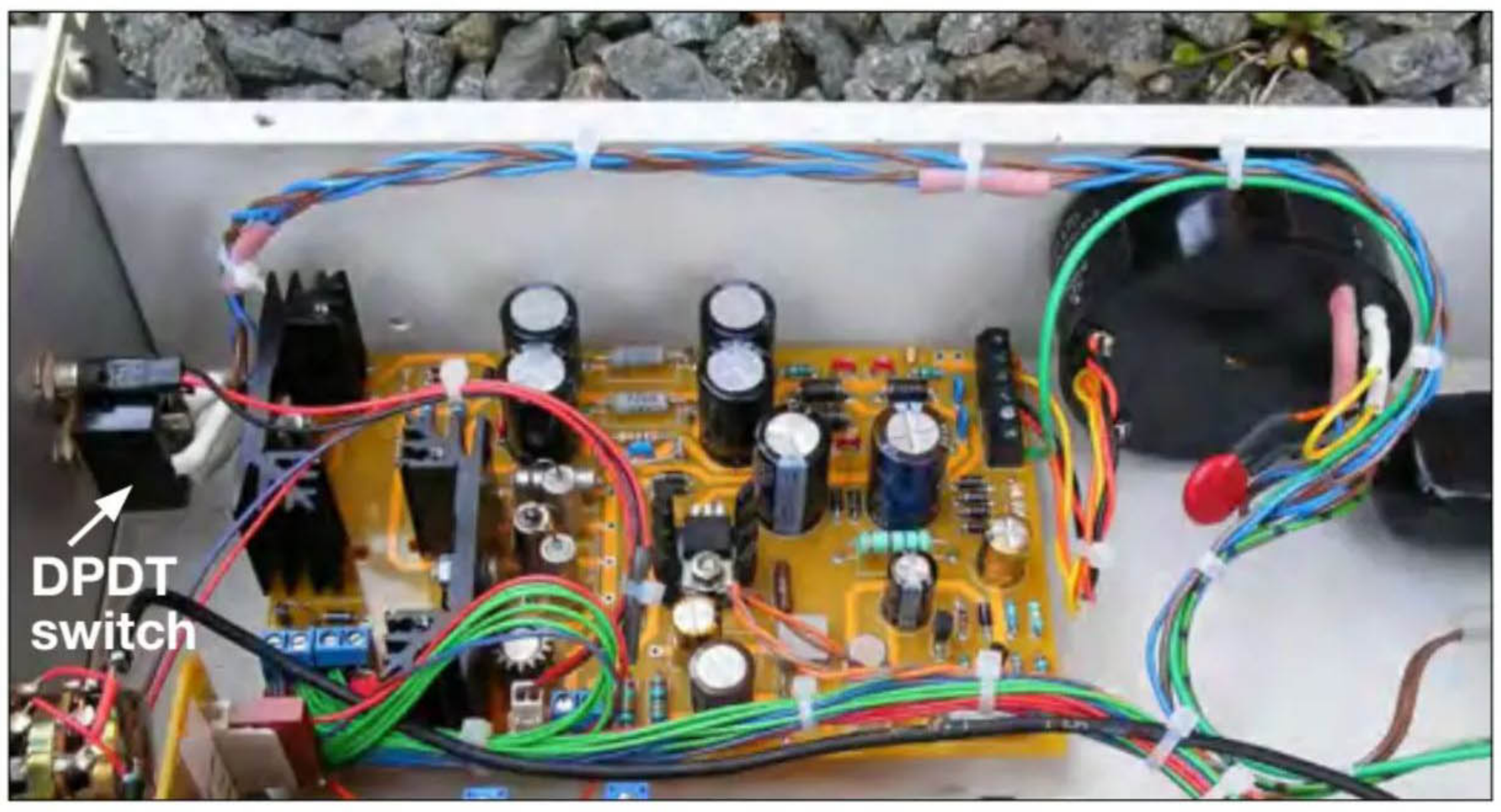


Fig.4. Mains switches need to be carefully wired to prevent hum emissions to the rest of the circuit. Note how wires to the black DPDT switch on the left are twisted and placed into the top corner of the enclosure.

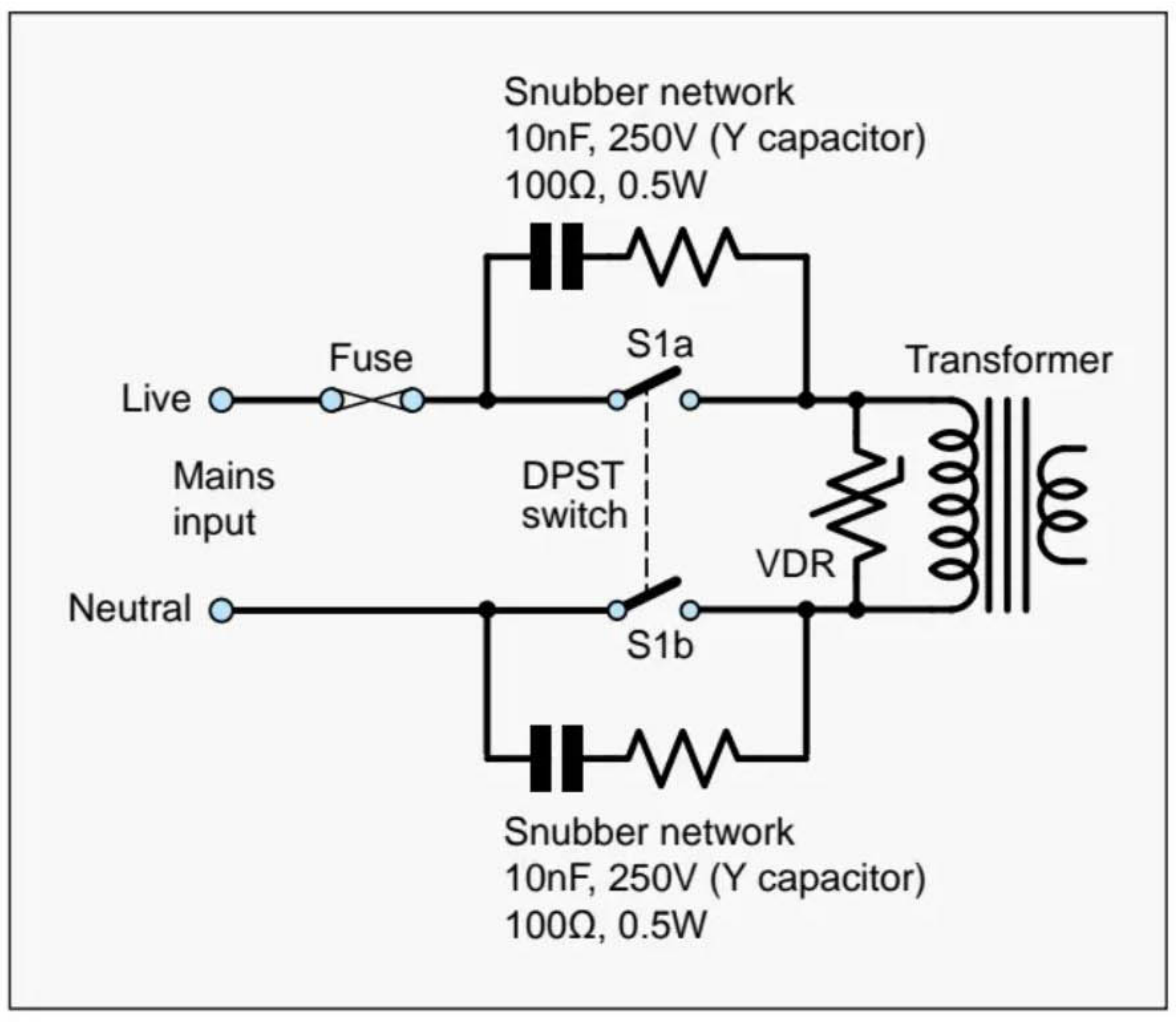
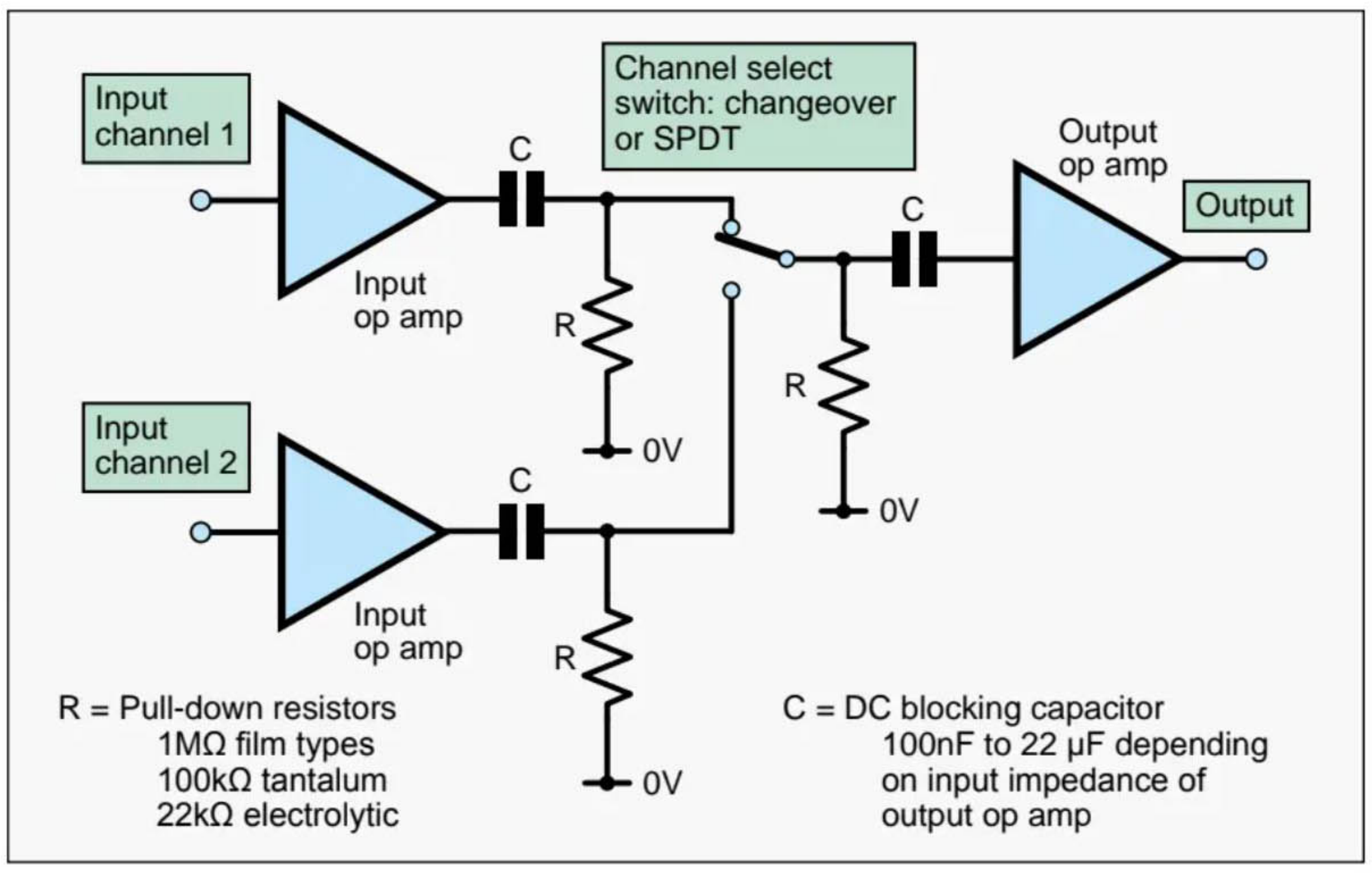


Fig.5. (left)To prevent loud cracks when turning off mains power, snubber networks can be used across the switch contacts.

Fig.7. (right)There must be no DC on signal lines to be switched or clicks will result.



safety compliance legal problems) are side stepped by buying in external DC 'wall-wart' power supplies.

Switch pops

Power switches need to be well suppressed to avoid generating audible pops and clicks. This is caused by arcing when switching inductive loads, such as transformers, generating electromagnetic interference. RC snubber networks across each contact are usually necessary to reduce arcing and subsequent noise. In-line mains EMI (electromagnetic interference, not the British record company) filters and voltage-dependent resistors (VDRs) normally complete the job, as shown in Fig.5.

Switches employing built-in mains neon indicators can also generate strange EMI noises from flickering as they age. To avoid the complexity of a mains-powered power-on indicator LED, it's always simplest to add the LED to the DC side of the power supply.

Quick-make, quick-break

Some power switches are designed to switch quickly regardless of how slowly they are moved. They have a spring mechanism which defines the switching time. This is important for some power applications, but I don't think it matters that much for audio. The slow ones tend to make fewer clicks and less mechanical noise due to the less abrupt transition. A 'snappy' sprung pair of contacts is shown in Fig.6.

Electrical vs electronic mains switching

These days, a solid-state power switch, such as a zero-crossing triac circuit can be used for mains switching. These can give click-free performance and allow cheap (low-current, momentary, push) switches to be used rather than a clunky latching mechanical type. The problem is that the UK Health and Safety Executive (and others) do not consider silicon to offer proper safety isolation because semiconductors fail short circuit, so an additional mechanical switch is still needed. (Electronic signal switching, as opposed to mains switching, using FETs is a whole subject in itself, which we will come to later.)

Clicks

When switching audio there must be no DC present on the signal or a click will be generated. Even a few millivolts of DC offset or capacitor charge is going to cause an equal voltage pulse when switching occurs. It will also have very fast rise and fall times creating a lot of audio bandwidth high frequency signals, which are clearly audible as a characteristic 'click'. This is the bane of audio signal switching and audio circuit designers go to great lengths to isolate DC by using coupling capacitors and pull-down resistors on every input and output, as shown in Fig.7. Electronic and relay switching has the additional problem of the control signal breaking through, giving the possibility of more clicks and thumps.

Latching vs momentary

Audio engineers like to be able to see what position a switch is in, and they like it to stay there, even after power loss, which means they have a strong preference for latching-type switches. Momentary push switches should only be used for doorbells! For audio, switches ought to have an accompanying LED and mechanical 'memory'. Unfortunately, latching mechanisms add mechanical complexity, cost and lower reliability, meaning they fail sooner. A lifetime of 25,000 operations is typical for a good quality switch. Consumer latching types last about 10,000 cycles, making the switch the shortest-life component in most audio systems.

The most cost-effective switch in the world is the 'tact' switch used in car key fobs. I use one in my *Stylophone Theremin* for the sound trigger with a big moulded springy plastic button on top. (Fig.8) After testing lots of switches with differing torque ratings/actuation pressures we found

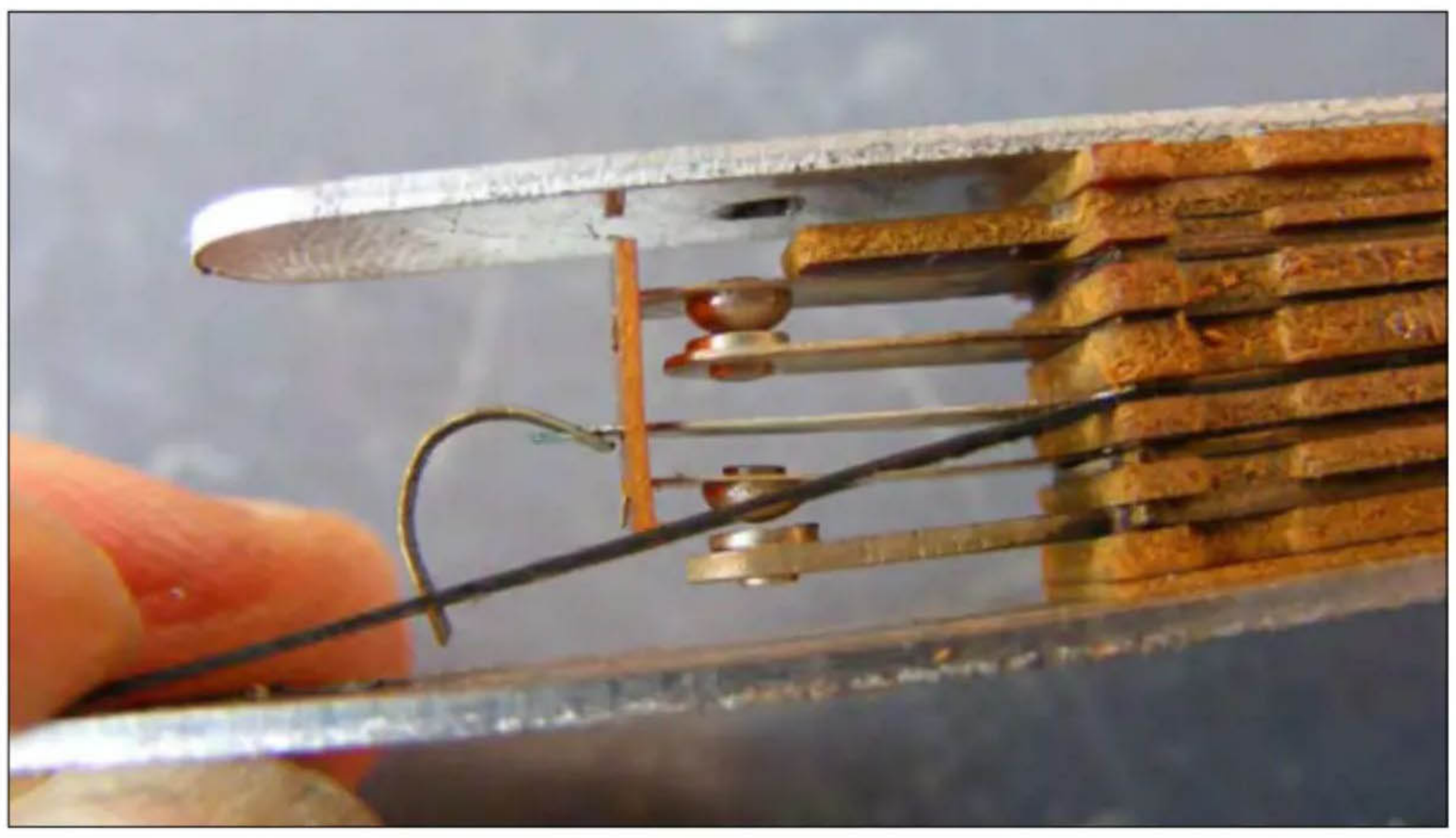


Fig.6. Close-up of switch contacts showing hysteresis-curved spring mechanism to ensure snappy action. Ideally, the contacts should be gold plated to reduce oxide build up.

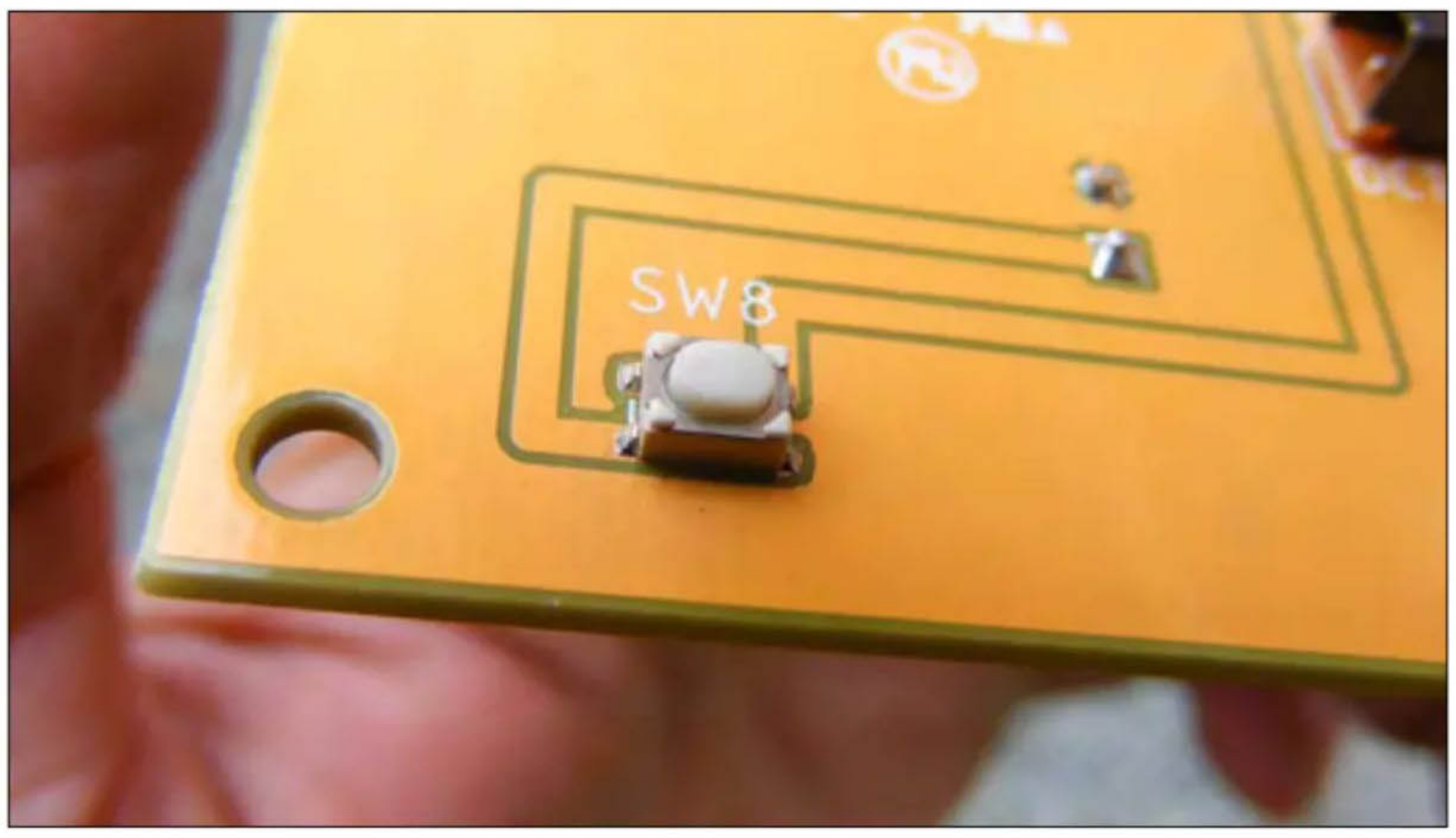


Fig.8. Momentary tact switch; these are used for the trigger button on the *Stylophone Theremin*. They are very cheap and available with different push-to-operate force options.

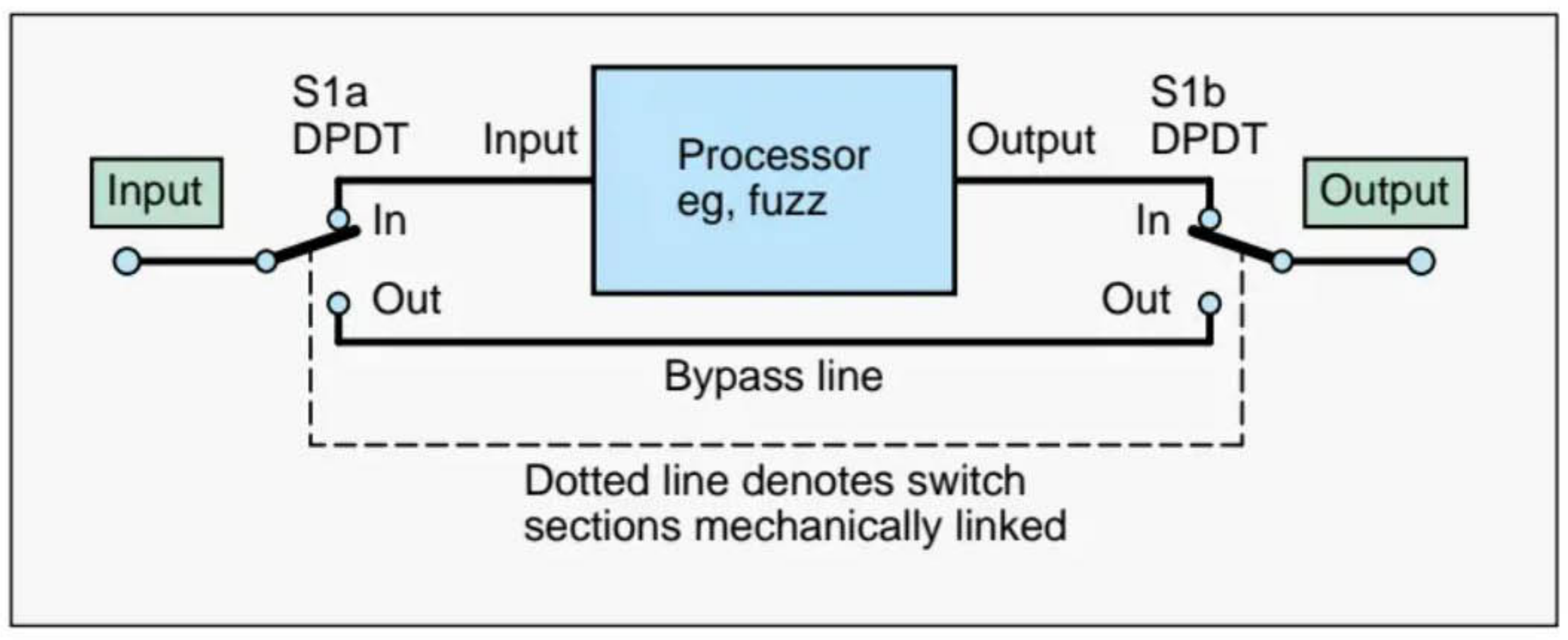


Fig.9. The classic 'hard-bypass' circuit for switching in and out a signal processor or effect.

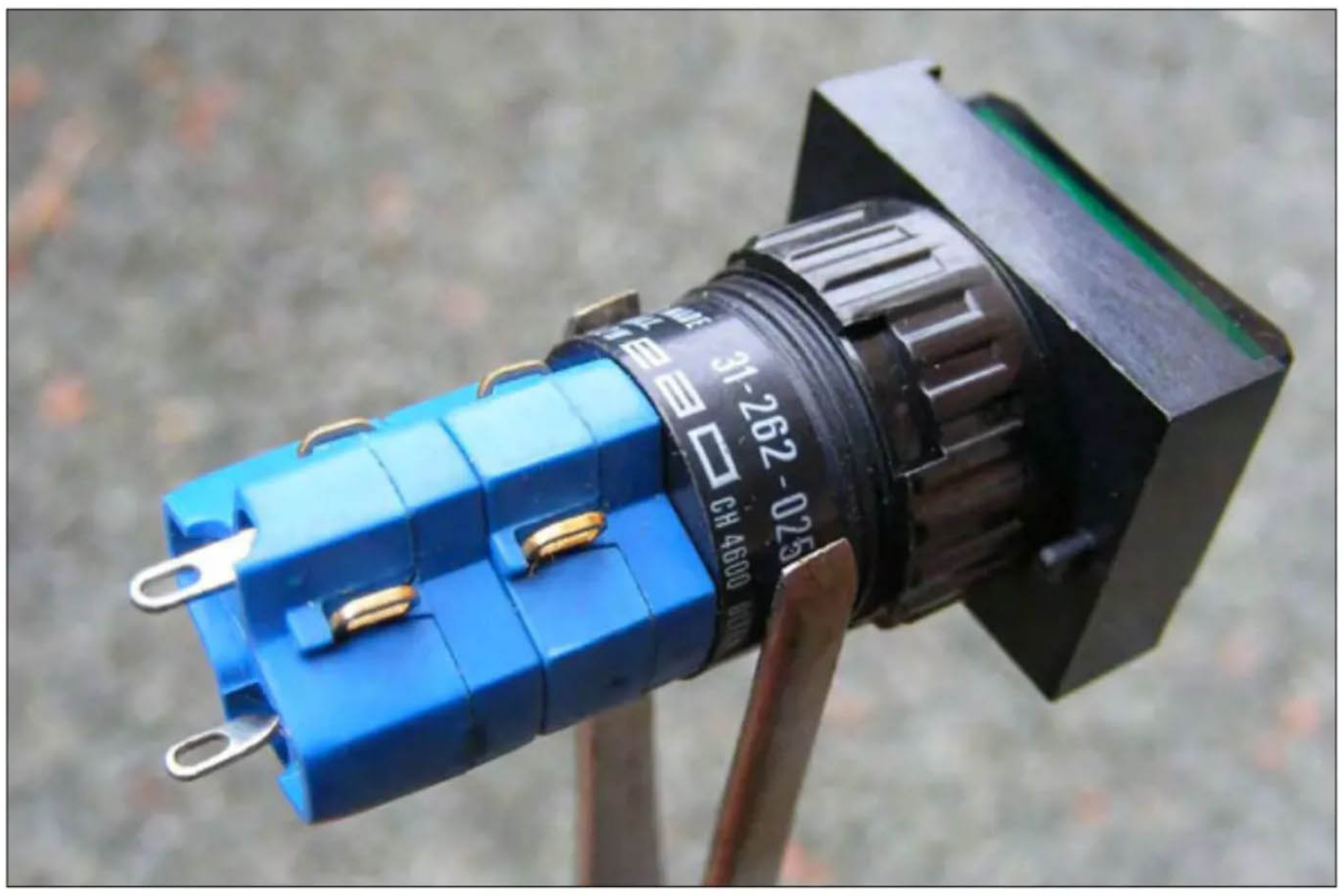


Fig.12. The 1,000,000-cycle EAO pushbuttons are Swiss made with a price to match, but they give your front panels that Star Trek console look. These industrial-type switches are made by several companies. Most are illuminated, often by odd filament bulbs, such as T5.5 types.

a combination of switch and moulding that gave a 'musical feel' at minimal cost.

Contact material

For low-level audio signals (<100mA, down to µV levels), gold-plated contacts ensure low distortion since gold does not oxidise. It has to be reasonably thick (5µm) or it may wear off when switching high currents, which will 'burn' the gold off the contacts. Silver-plated contacts are the next best and can be used for high level (>1V) audio signals. In the presence of atmospheric pollution, such as from wood burners, diesel engines and cigarette smoke, black sulphide may form on silver contacts giving rise to crackles and distortion. These contacts need to be cleaned with a contact cleaner such as Kontakt 60, then lubricated with Servisol or Kontakt 10 Super. Some switches have self-wiping contacts which maintain good conductivity so long as they are moved regularly. Alps-style pushbuttons (the manufacturer, not the mountain range), slider and rotary types have this feature. Toggle switches, rockers and pushbuttons generally don't and thus have shorter lives.

Poles, ways and odd acronyms

If a switch has two switch positions then it is often described as a 'changeover' (C/O or CO) switch or 'double throw' (DT). I suspect this is a throwback to the old knife switch design (Fig.1). Two-section changeover switches are often called 'double-pole, double-throw' or DPDT, these are the most common types in audio systems. A classic circuit is the effect in/out switch used on guitar pedals shown in Fig.9. It's also useful for the motor direction reversing, channel-flip or phase-change circuit shown in Fig.10. It can be used as a left/right channel flip. It's easy to wire up, as shown in Fig.11. Lighting designers and electricians know them as an 'intermediate switch', often used on stair landings.

Normally closed (NC), normally open (NO)

No, we're not talking about provincial British tea rooms; normally closed (NC) and normally open (NO) are standard switch nomenclature referring to the default switching position. A lot of pushbuttons, such as the Eao types shown in Fig.12, have an NO and NC pair of contacts in each section. These can be joined together to make a changeover switch, as shown in Fig.13.

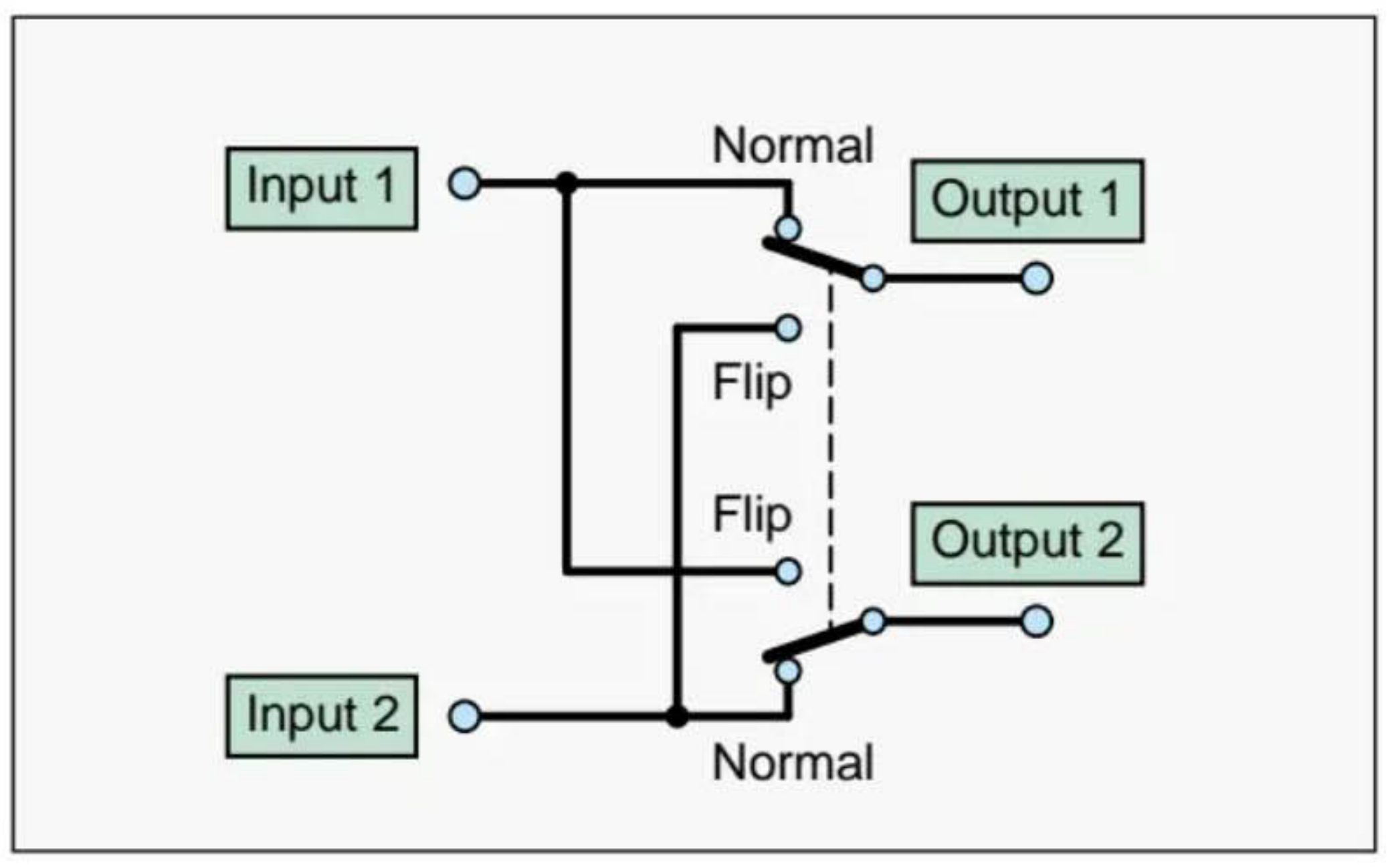


Fig.10. (above) The phase flip circuit which switches over two lines. It could be used to flip the phase of a loudspeaker.

Make before break (MBM), break before make (BBM)

MBM and BBM are not fancy food fads, but defined forms of switching action. Most switches break from one contact before they move onto the next, thereby maintaining isolation – a switching action called 'break before make' or 'BBM', as shown in Fig.14. Occasionally, on some switches with sliding contacts it can still be joined to the previous contact as it moves to the next one. This is achieved by making the wiper wider than the spacing between the contacts. This is called 'make before break' (MBB), or shorting contact. MBB can be a useful property in audio switching, providing a seamless transition from one signal source to another, often with less chance of generating a click. MBB is also useful if you want to avoid big steps, intermittently down to zero between switch positions with multiple resistive steps, such as switched attenuators. The Fender Stratocaster guitar pick-up switch was originally a three position MBB switch. Guitarists soon realised they could move the switch to get unusual sounding phase cancellations in the 'intermediate' positions (Fig.15). Fender responded by making the switch have five positions.

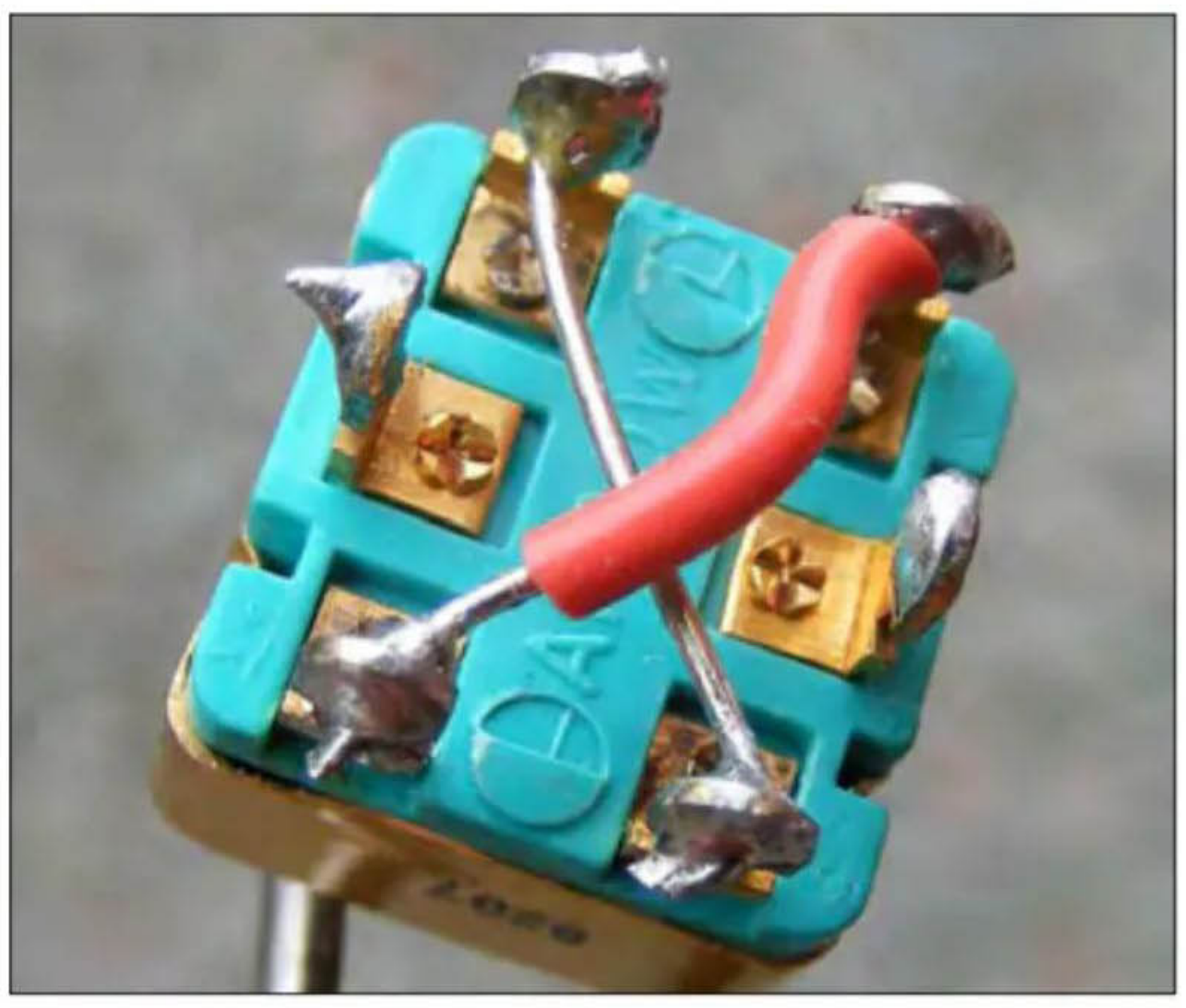


Fig.11. (right) Rear of a DPDT toggle switch wired for 'phase flip' action. Note the characteristic 'cross over' wiring. The two wires coming in go to the cross wires and the two wires coming out are taken from the centre tags. Electricians use an 'X' symbol to denote an intermediate switch pattern.

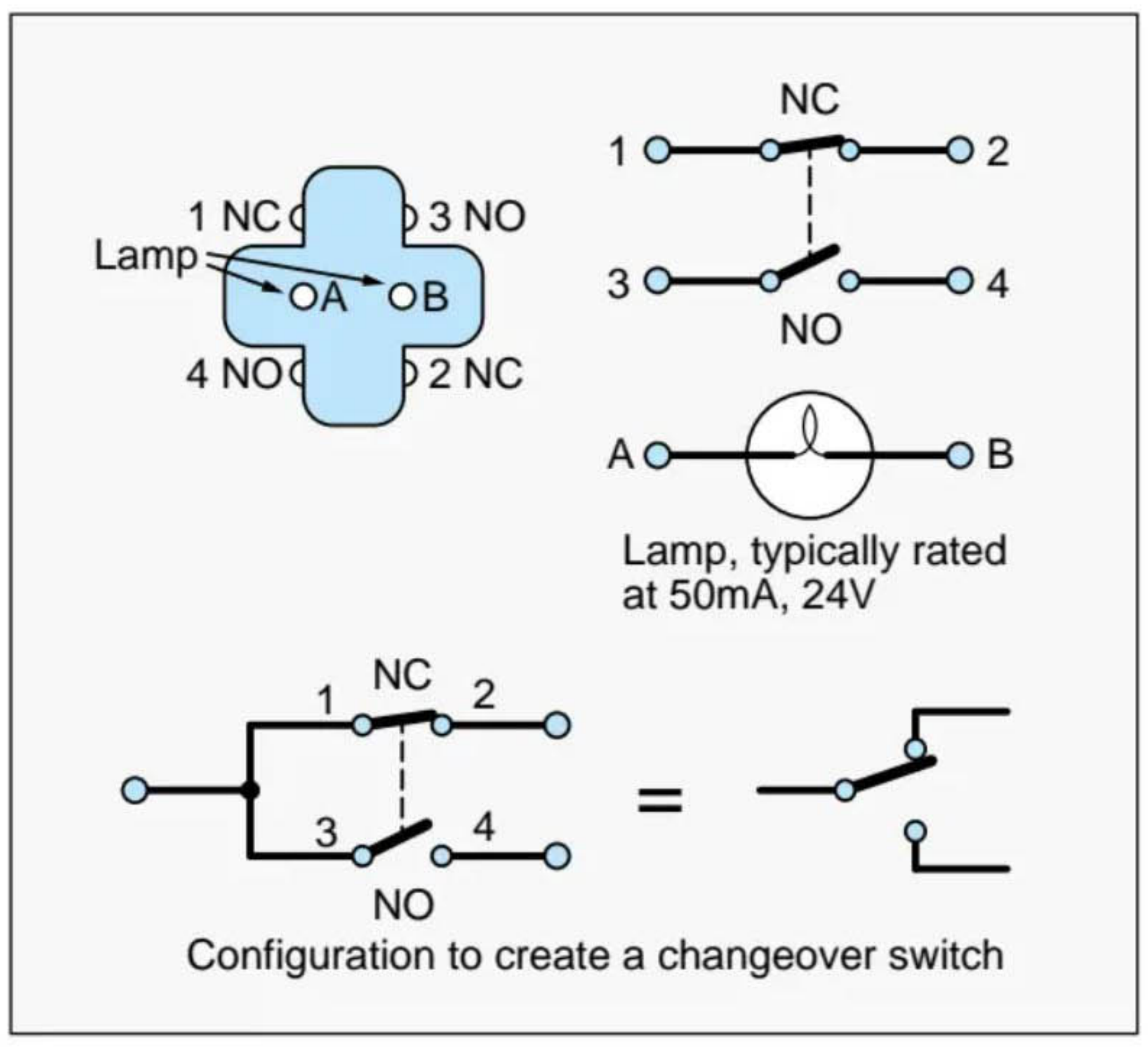


Fig.13. EAO pushbuttons (see Fig.12) and similar switches often have two sets of contacts per section. One is normally closed (NC) and one is normally open (NO). The NC and NO contacts change over when the button is pressed.

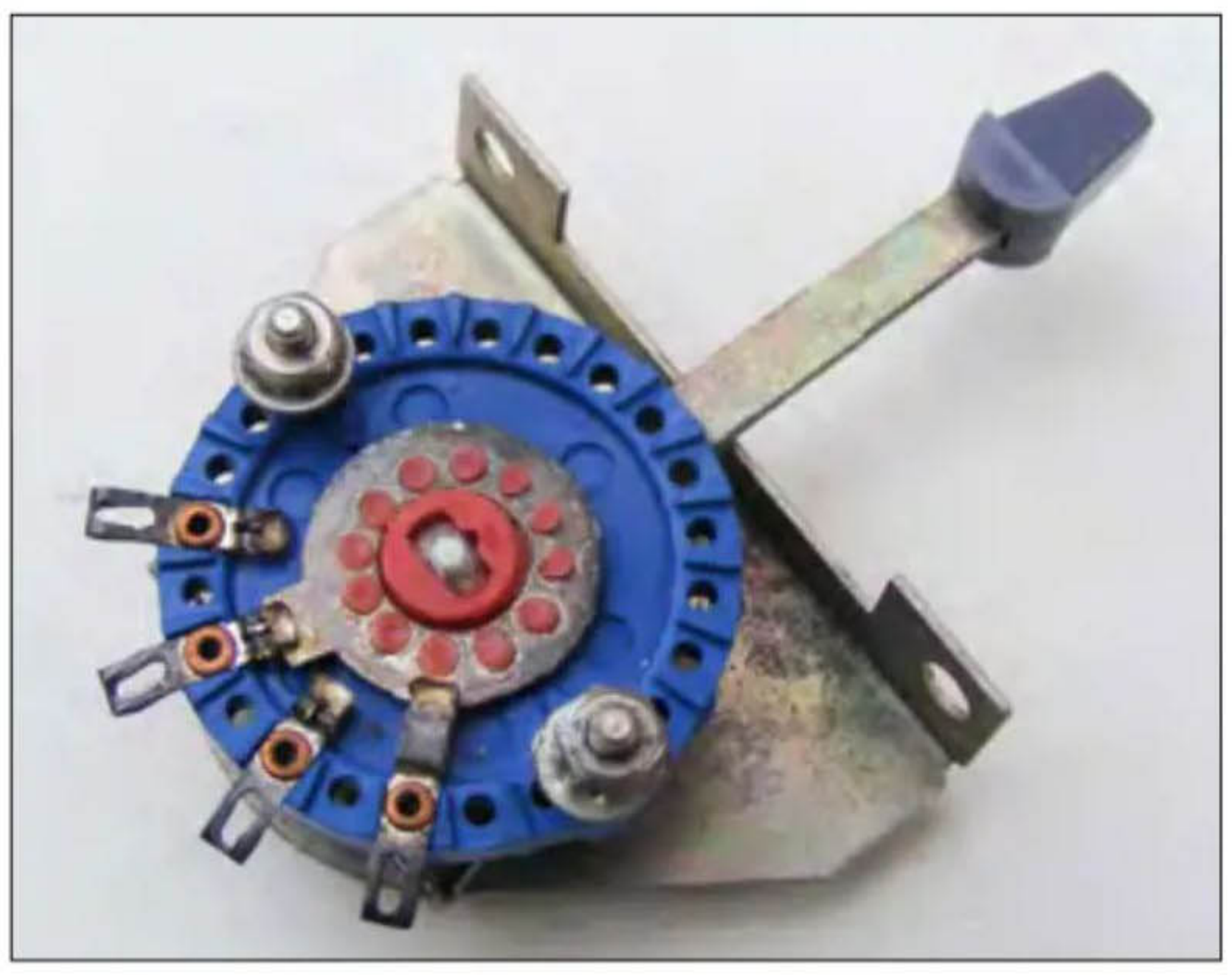


Fig.14. Make before break (MBB) contact.

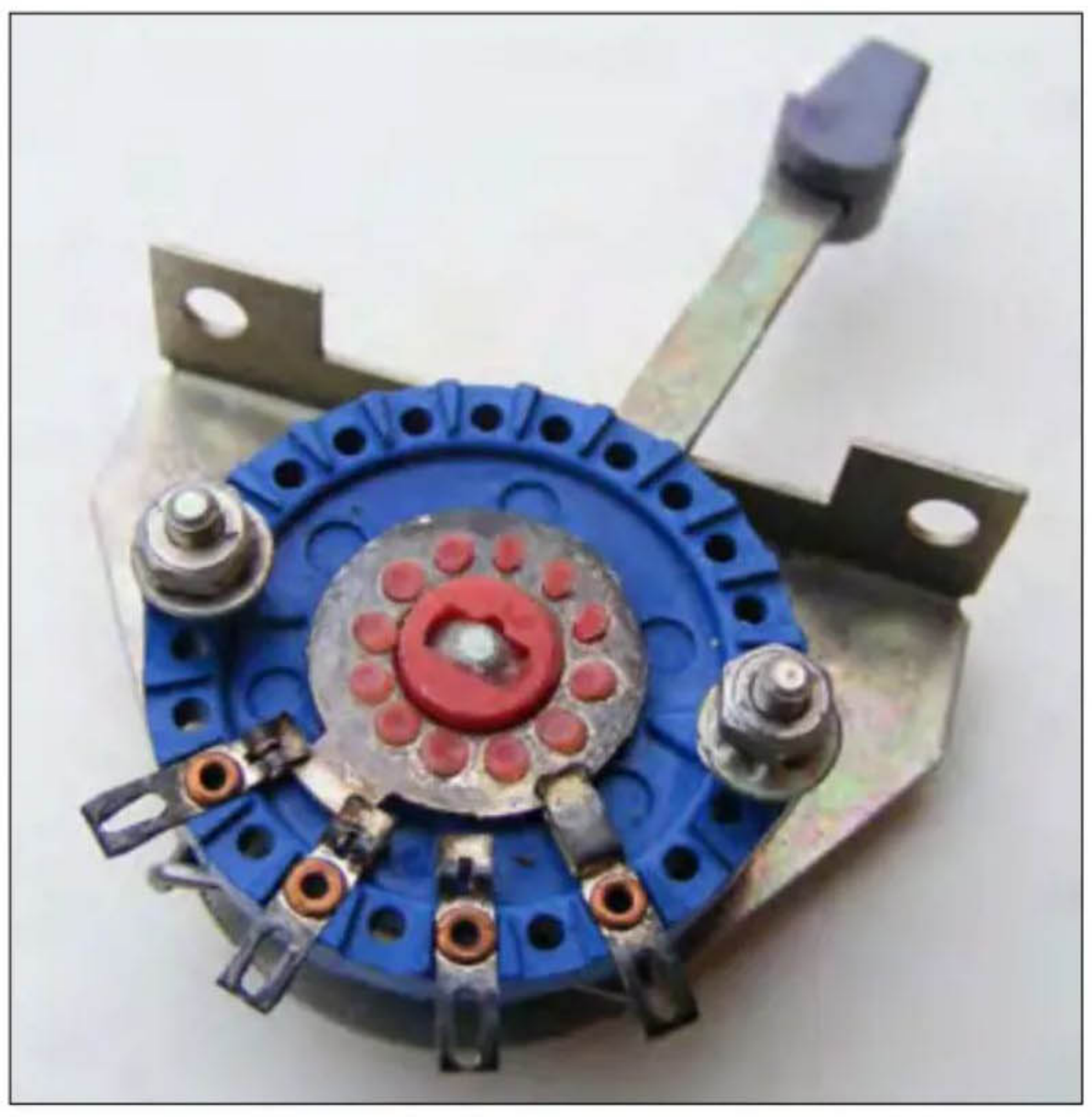


Fig.15. MBB moving contact in transition joining two switch positions in a Fender-style lever switch.

Toggles

Miniature toggle switches are the most popular switching device for small-production audio equipment because they are the simplest to use. One thing to watch out for is that the position of the closed contacts is usually the opposite to lever (or dolly as it is correctly called), as shown in Fig.16. This is not normally a problem since the switch can be turned round if it's hard-wired. Since the tags form the internal contacts it can be assumed if they are gold plated the contacts are gold. One of my favourite toggle designs is the Arrow Hart Eaton TS6 shown in Fig.17. I've had some in continuous operation for 30 years.

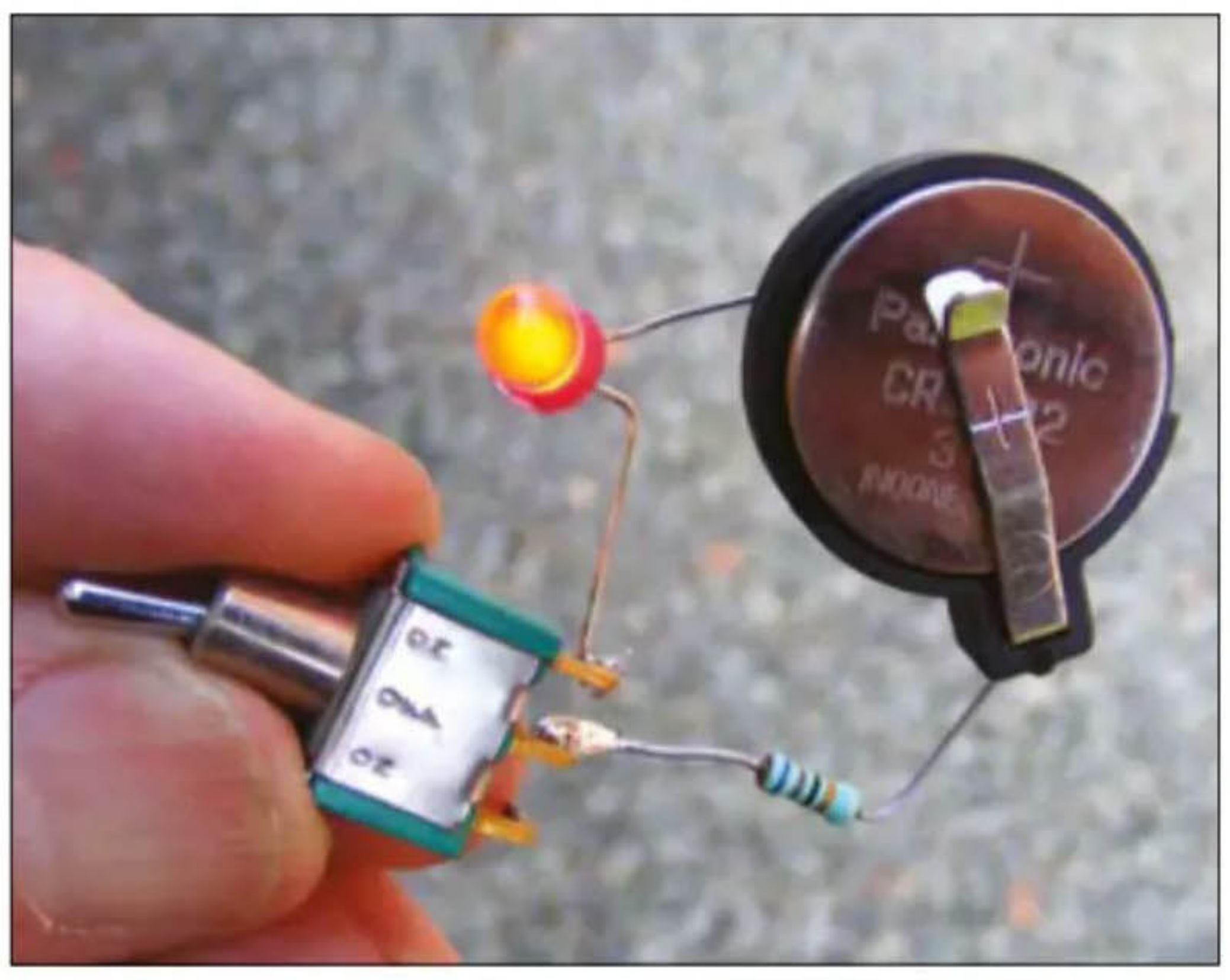


Fig.16. On most toggle switches, when the dolly is up, it's the bottom contact that is closed, and vice versa. Make sure you get this right for PCB-mounted switches.

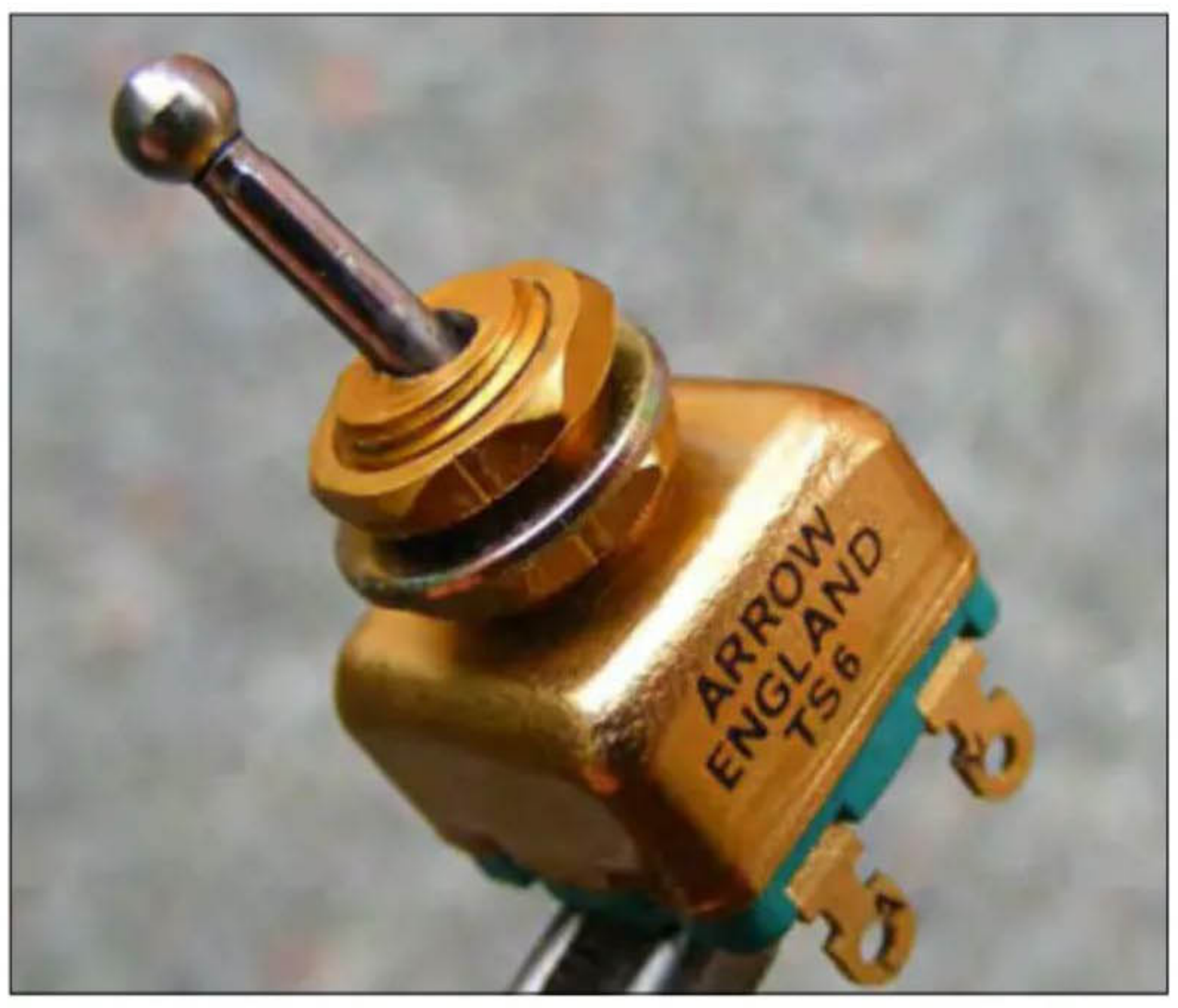


Fig.17. I use these Arrow TS6 toggles in top-quality studio gear. They are now made by Eaton/Hart.

Centre-off

You can get toggle switches with three positions, the middle one is centre off, described as ON-OFF-ON. These are useful for selecting, say channel one for up, middle for mute and down for channel two.

C&K

C&K are a US company which makes some of the best toggles switches. They do a special type of DPDT switch (such as their 7211 shown in Fig.18) that looks like a centre off type and has a very versatile (but confusing) contact arrangement, as shown in Fig.19. This is called an ON-ON-ON switch. These can be used to give an interesting set of series parallel variations of pick-ups in electric guitars.

Biased operation

Toggle switches can also come with a momentary option called 'biased', which means it can be moved to an on position but springs back when released. It is possible for the switch to be biased in one position and latching in the other. This would be called an (ON)-OFF-ON switch which would be centre-off with the brackets denoting the momentary or biased position. I used one of these on a music sequencer where the biased position is used to increment the next step for tuning the note; centre is off, and 'on' cycles through the steps once the notes ae all tuned. I've also employed them as quick trigger-off-continuous drone switches for synths.

Slide

These are the cheapest switches for production audio equipment. They came to popularity as wave-change switches in cheap radios. They are often found in three-position versions, used with the LW/MWFM selection in mind. It's easy to see what position they are in, but they are prone to dirt ingress, so it's worth moulding a protective top to stop this and at the same time add a larger actuator. Sliders need tidy punched rectangular holes, so they are only suitable for mass production. I used them in my recent Stylophone theremin, as shown in Fig.20.

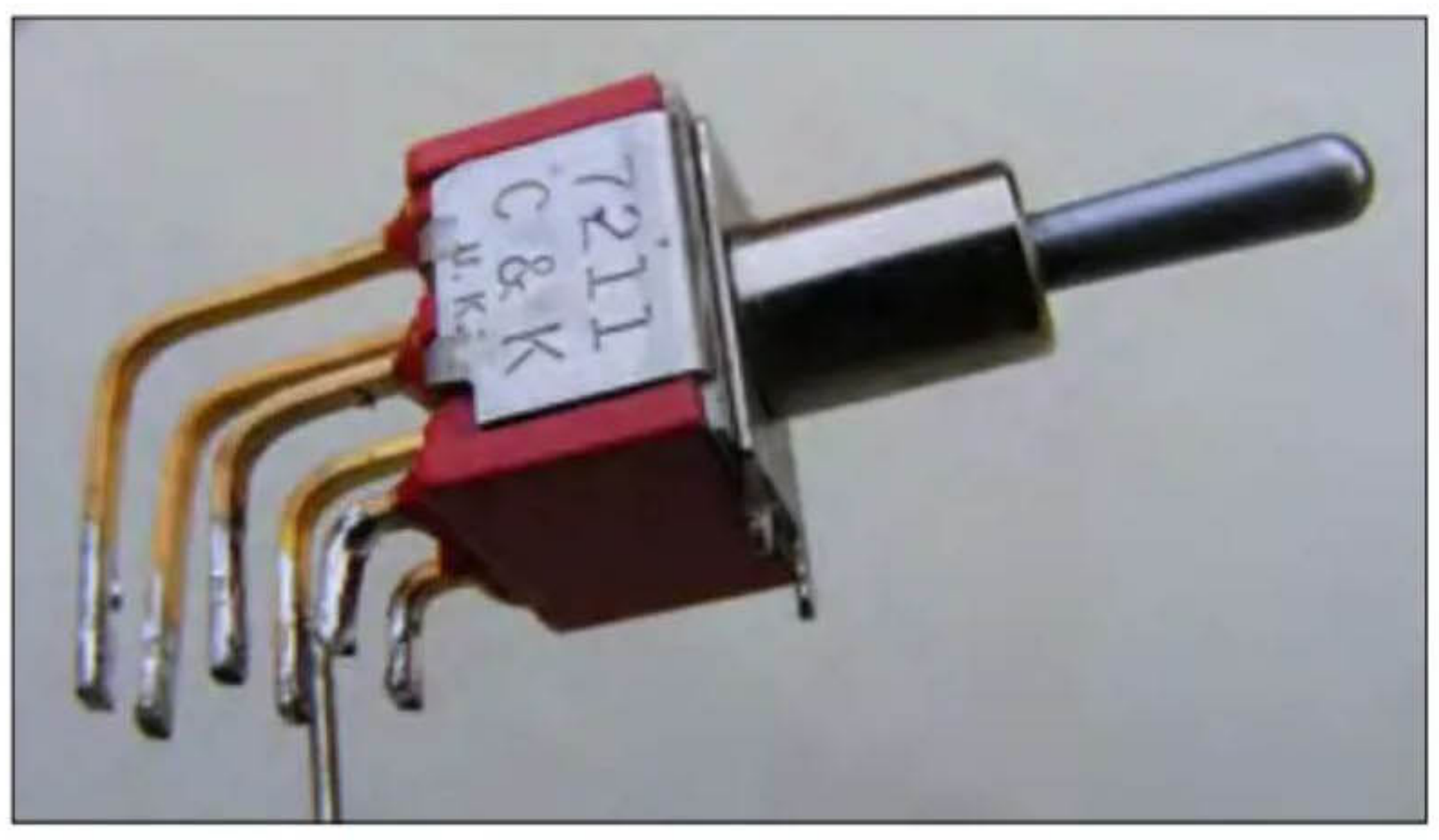


Fig.18. C&K were the original manufacturers of some of the best miniature toggle switches. You can spot them from their distinctive dark red mouldings that don't melt. This is a 7211 PCB-mount right-angle toggle switch, many of which I installed in RTS intercom belt-packs used in the TV industry. Note the unthreaded bush – no nut is needed, just big plated-through PCB holes.

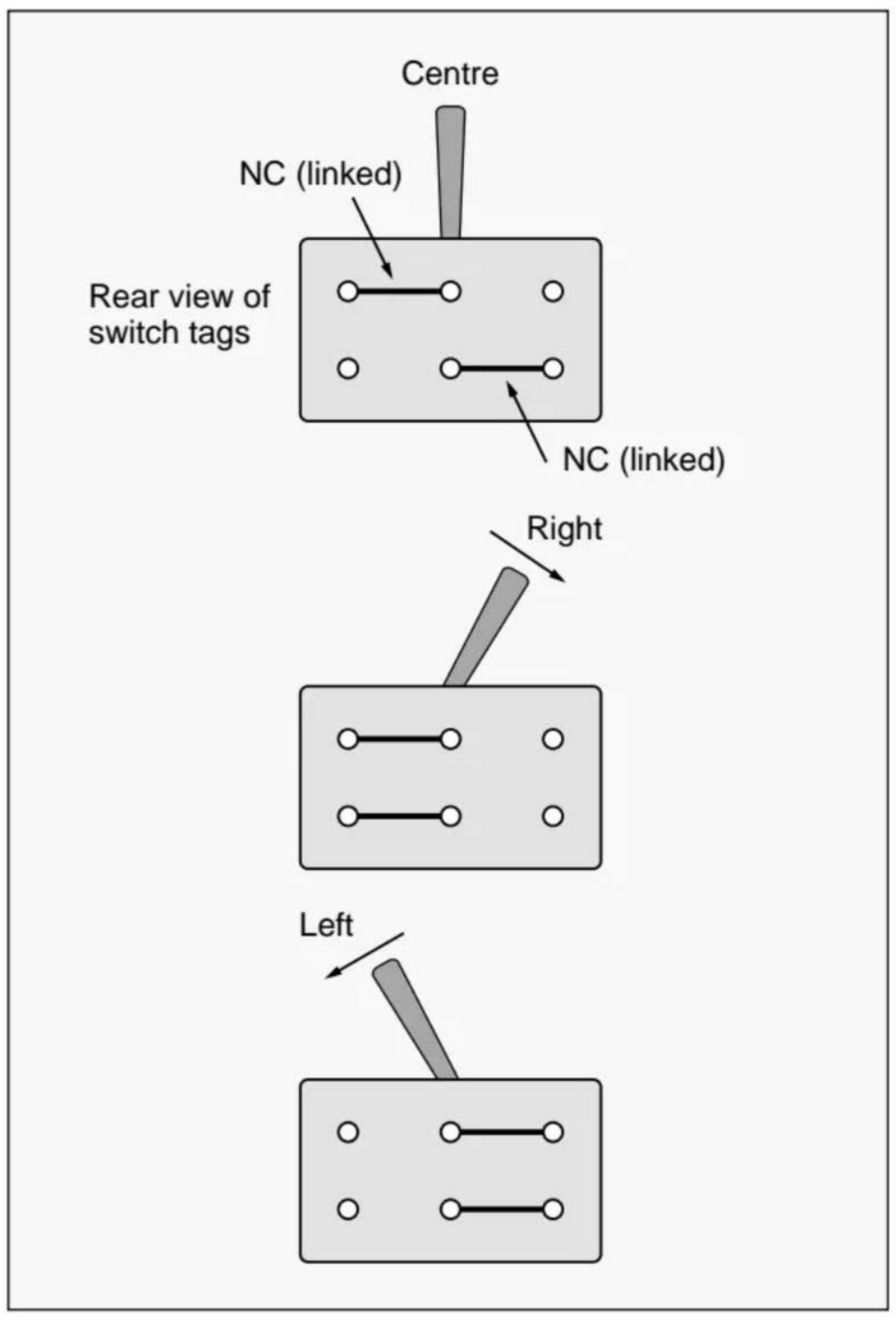


Fig.19. Contact positions for C&K style DPDT ON-ON-ON switches.

Next month

In *Part 2* next month we have a little more mechanical switching to cover before we move on to the important subject of audio 'silicon switching'.

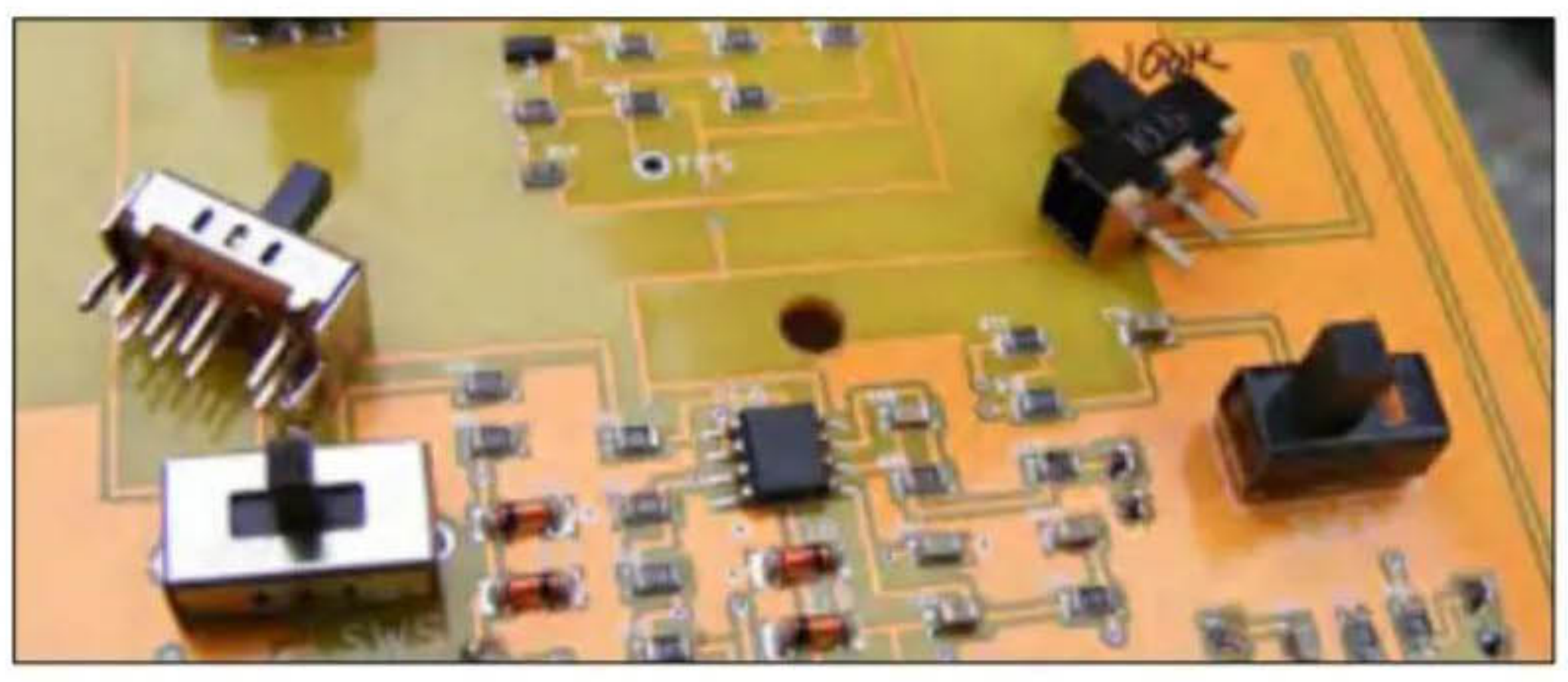


Fig.20. Slider switches can do a lot for low cost. I used these on my price-barrier-smashing *Stylophone Theremin*. (Product of the year at NAMM show!)

AOShop

The home for specialist audio, analogue and historic components – provided by Jake Rothman, *PE's Audio Out* columnist. The AOShop is your best bet for classic analogue 'NOS' (new old stock) components, including all parts for *Audio Out* projects and designs.

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Note '10/63' denotes '10µF 63V'.

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22/35, 33/35, 47/20, 68/15, 100/10, 150/6	£1.25
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Kemet axial 6.8/10	£0.30
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Tantalum bead

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Hughes 540/10	£3.20

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Hermetic bipolar tantalum 16/35	£3.20
Elcap axial 10/50	£0.50
Generic radial 100/16, 470/35, 100/ 63, 22/35, 4.7/35, 220/16	£0.50

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Mica 1-12pF, 2-40pF	£1.00

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A13	£2.00
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48V PSU (*EPE*, 2019)	£3.00
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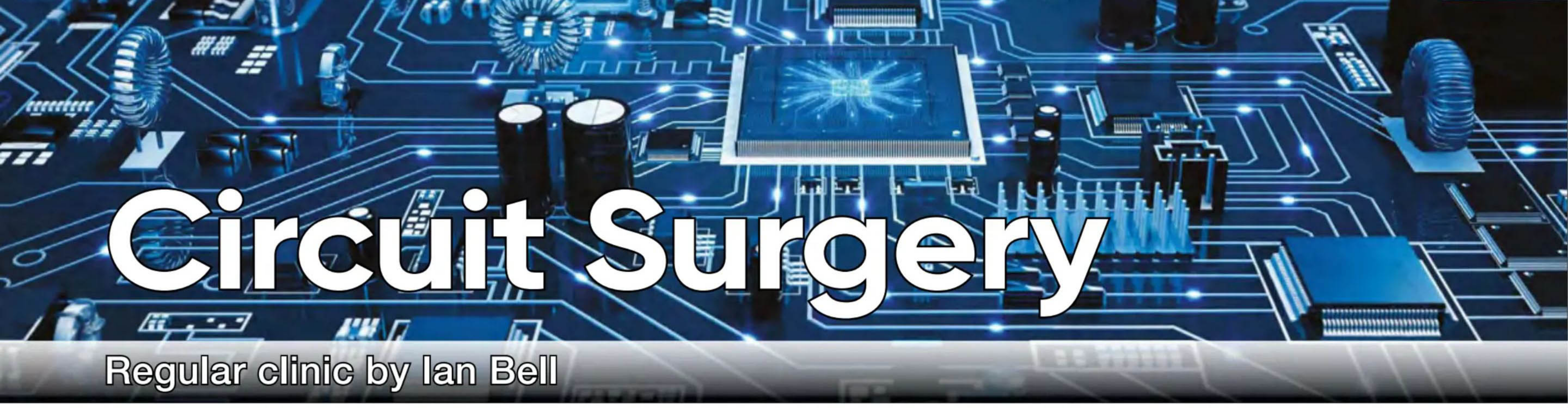

Circuit Surgery

Regular clinic by Ian Bell

Topics in digital signal processing – ADCs

We are looking at various topics related to digital signal processing (DSP). DSP covers a wide range of electronics applications where signals are manipulated, analysed, generated, stored or displayed as digital data, but originate from, and/or are output as, real-world signals for interaction with humans or other parts of the physical world. Fig.1 shows the key elements of a generic DSP system with a signal path from an analogue input via digital processing to an analogue output. This does not necessarily represent every DSP system (not all have all the parts shown) but it serves as a reference for the various subsystems we will look at.

Last month we looked at sampling. We have not discussed all the details of input filtering and the sampling process yet, but at this point it is useful to look further down the signal path to the analogue-to-digital converter (ADC) due to its fundamental role in the digitisation of analogue signals.

Quantisation

In a similar way to the finite time step limitation discussed last month, there is also a finite limit on the number of different values a digitised signal can take. This shift from a very large (or effectively infinite) set of possible signal values to a smaller one is called 'quantisation'. It is similar to the rounding of values in numerical calculations. Digital hardware (and the software running on it) can handle numerical calculations which have a very large number of possible values. The level of numerical detail used is referred to as the precision (eg, how many decimal digits a number can represent). Increasing precision requires more hardware and/or more processing time (or more speed to process a given amount of data in a given time).

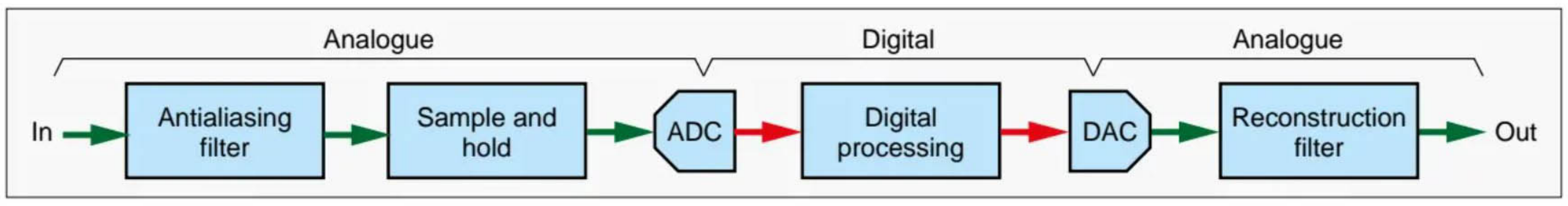

Fig.1. Generic DSP system structure.

Digital hardware and software considerations may limit the number of possible values per sample that is practical in a given DSP system, but the limit (at the point the signal is digitised) is more likely to be determined by the choice of ADC (availability and affordability in the context of a particular design).

ADCs input an analogue signal and typically the output is a digital numerical value as a binary integer (whole number value). The number of possible values in a digitised signal is determined by the number of bits (binary digits) in the ADC's output. Specifically, for an N-bit output there are 2^N possible values. For example, for 10-bits there are $2^{10} = 1024$ possible values. Increasing the number of bits increases the demands on the analogue circuitry in the ADC. The more bits the smaller the input differences the ADC has to discriminate to correctly convert it to the digital code. Imperfections, errors and noise in the circuitry will reduce the obtainable precision, so more bits require better design and technology, and also generally leads to slower sampling rates.

Choosing ADCs

There are a large number of ADC integrated circuits on the market, so there is plenty of choice and variety. To find a device to suit your needs, as with other ICs, you can visit the website of IC manufacturers (for example, Analogue Devices at **www.analog.com** and Texas Instruments at **www.ti.com**) or component distributors (like Farnell and RS) where you can find selection tables which you can sort according to device parameters (such as number of bits and maximum sampling rate) as well as finding price and availability information.

Analog Devices is a leading manufacturer of data converters. At the time of writing they provide ADCs ranging from 6 bits up to 32 bits. Generally, 24-bits is the maximum for a 'standard' ADC – the 32-bit devices use oversampling – they input samples at a much faster rate than they output them, which facilitates reduction of noise and improves effective resolution. Analog Devices' ADCs have speeds ranging from around two samples per second to over 10 giga samples per second (GSPS). The extremes relate to devices aimed at specific purposes – high-precision sensing applications at the slow end, and the fastest for advanced RF signal processing systems such as satellite communications. The latter devices cost in the low thousands of pounds, but of course there are many inexpensive ADCs for more everyday projects.

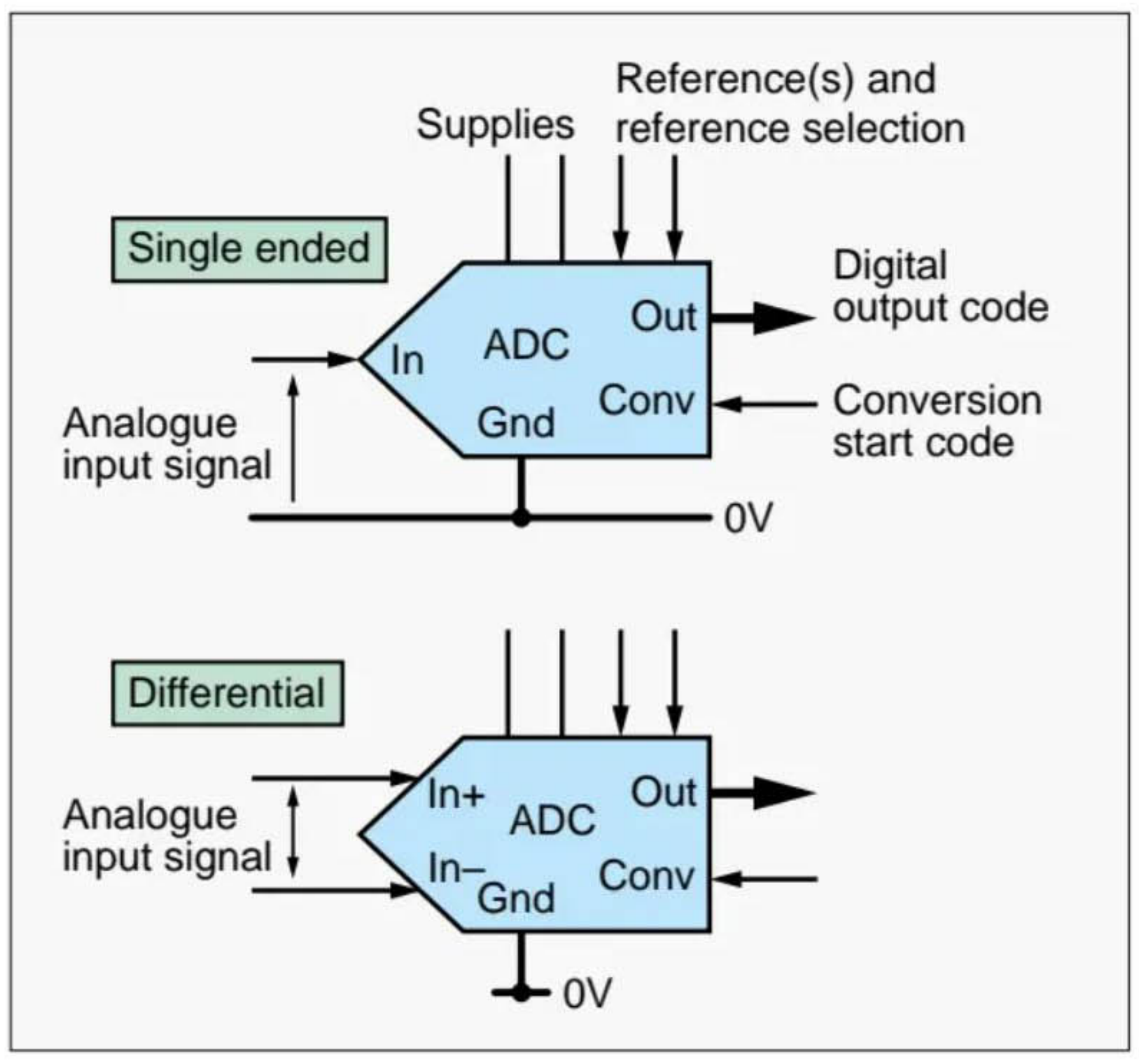

Fig.2. Generic schematic symbols for ADCs.

ADCs are often used with microcontrollers and are typically connected to the microcontroller via a standard serial bus such as SPI or I²C. A few ADCs with parallel outputs are also available. As well as separate, standalone ADC ICs there are often ADCs built into microcontroller devices. These generally have moderate capabilities but are suitable for many projects and help reduce cost, complexity and component count. If a suitable microcontroller and on-chip combination is not available, then one of the many discrete ADCs mentioned above can be used.

ADC connections and signals

Fig.2 shows generic schematic symbols for an ADC – not all the signals shown may be actual pins

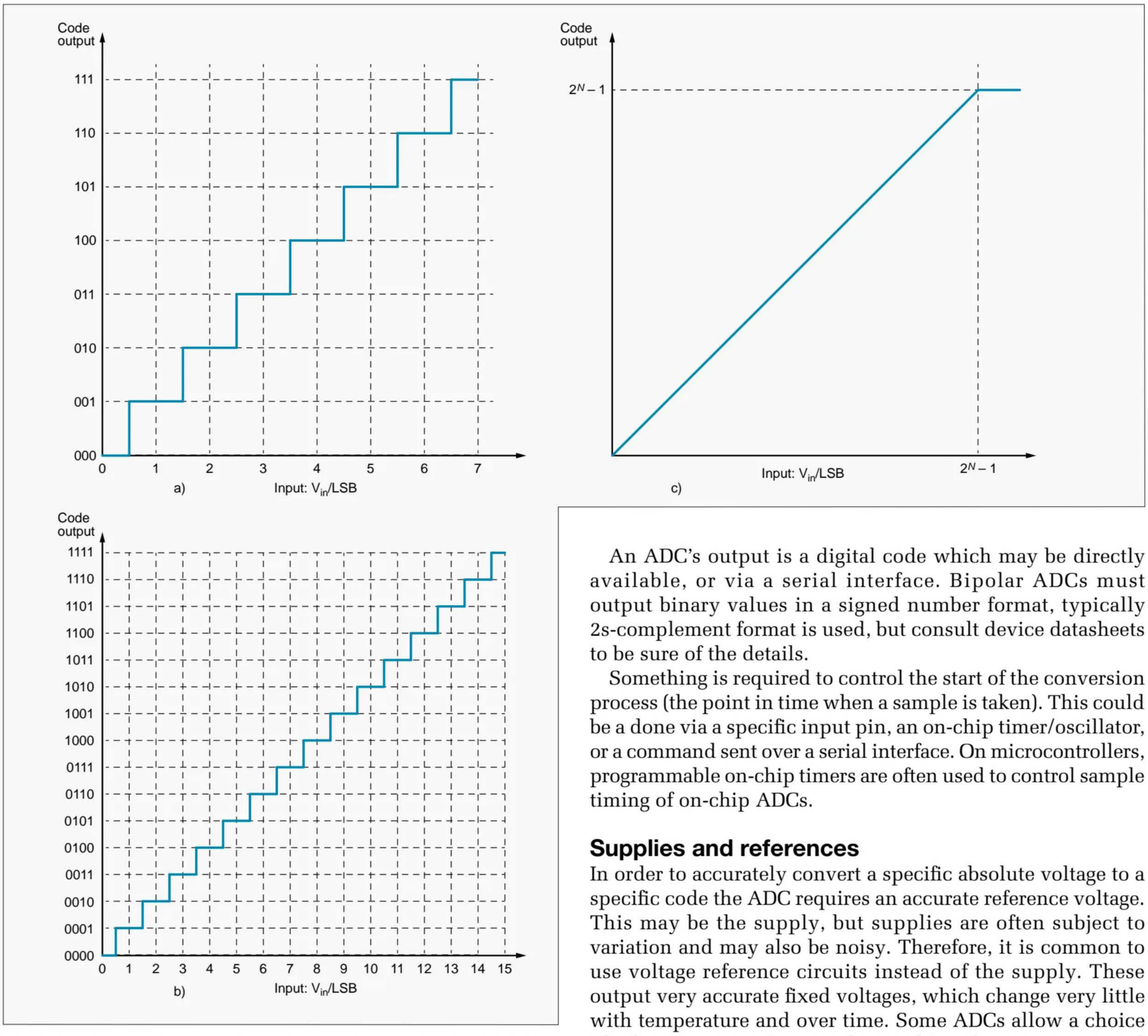

Fig.3. Input-output (transfer) function for ADCs (a) 3-bit ADC (8 output codes), (b) 4-bit ADC (16 output codes), (c) ADC with a (near) infinite number of bits, *N* – this is the ideal 'straight-line' transfer function.

– the functionality can be obtained via commands over a serial bus. ADCs may have one or two inputs for the signal being converted. One input is referred to as 'single ended' and two as 'differential'. For single-ended inputs the value converted is the input voltage with respect to ground, and for differential it is the voltage difference between the two inputs $(V_{in+} - V_{in-})$ which is converted. Single-ended circuits are simpler but differential inputs provide the ability to reject (cancel out) signals which are common to both inputs (common-mode rejection).

Some ADCs have differential inputs which have a restricted range of voltages on one of the inputs, typically tens or hundreds of millivolts with respect to ground. These are called pseudo-differential inputs. One of the 'pseudo-differential' inputs is effectively ground but the differential nature of the inputs still provides common-mode rejection. Fully differential ADCs allow a wider range of voltages on both inputs. ADC inputs (both single ended and differential) may be either unipolar or bipolar. Unipolar inputs only allow voltages of one polarity (typically positive with respect to ground), whereas bipolar inputs can be positive or negative.

An ADC's output is a digital code which may be directly available, or via a serial interface. Bipolar ADCs must output binary values in a signed number format, typically 2s-complement format is used, but consult device datasheets to be sure of the details.

Something is required to control the start of the conversion process (the point in time when a sample is taken). This could be a done via a specific input pin, an on-chip timer/oscillator, or a command sent over a serial interface. On microcontrollers, programmable on-chip timers are often used to control sample timing of on-chip ADCs.

Supplies and references

In order to accurately convert a specific absolute voltage to a specific code the ADC requires an accurate reference voltage. This may be the supply, but supplies are often subject to variation and may also be noisy. Therefore, it is common to use voltage reference circuits instead of the supply. These output very accurate fixed voltages, which change very little with temperature and over time. Some ADCs allow a choice of reference source (eg, supply, on-chip reference, or external reference via device pins). Using the supply as a reference works best if the value converted is effectively a ratio of the supply (eg, via a resistive sensor in a potential divider) because supply shifts have the same relative effect on the ADC and measured value, so the effect of supply shifts cancels out.

ADCs may have a simple single supply pin, or there may be multiple supplies. This might include positive and negative supplies for bipolar devices and separate supply pins for the analogue and digital parts of the chip. The latter may be due to different operating voltages, but using separate supplies also helps prevent noise from digital switching disturbing the analogue circuitry.

ADC transfer functions and LSB

Fig.3 shows the input-output relationship for three data converters. In all cases the input is an analogue voltage, and the output is a digital code. An ADC transfer characteristic has a staircase shape. The more bits in the output code the more steps we get in the complete transfer characteristic, as can be seen by comparing the 3- and 4-bit characteristics in Fig.3a and Fig.3b. If we had a (near) infinite number of bits in the output code the transfer characteristic would be a perfect straight line as seen in Fig.3c.

As indicated above, the range of analogue input voltages over which an ADC performs conversion (the full-scale range

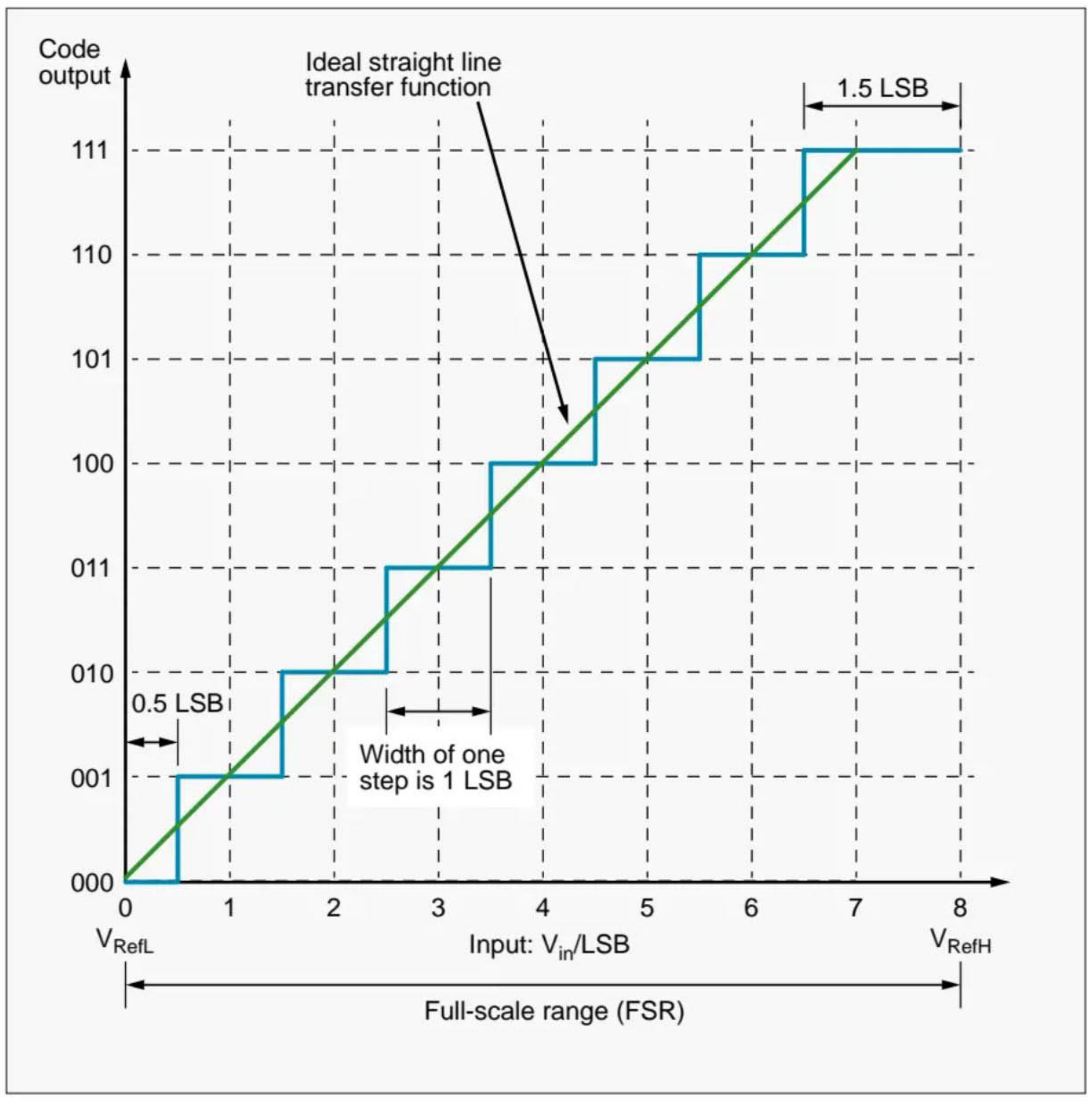

Fig.4. Details of a unipolar mid-tread ADC transfer function.

– FSR) is set by two reference voltages in the ADC circuit – the low reference voltage (V_{RefL}) and the high reference voltage (V_{RefH}), see Fig.4. Often the low reference is ground, but it does not have to be. An N-bit ADC converts analogue input data into 2^N codes. The voltage difference between *adjacent* codes is called the 'least-significant bit' (LSB), which is given by:

$$LSB = \frac{(V_{\text{RefH}} - V_{\text{RefL}})}{2^N}$$

For example, if a 12-bit ADC has $V_{\text{RefL}} = 0$ and $V_{\text{RefH}} = 5\text{V}$ then the LSB is given by:

$$LSB = \frac{5}{2^{12}} = \frac{5}{4096} = 1.22mV$$

The transfer functions shown in Fig.3 and Fig.4 have the first transition 0.5 LSB above the bottom end of the FSR and the final transition 1.5 LSB below the top of the FSR. This is a common approach and is referred to as a 'mid-tread' transfer function because the point in the middle of the FSR at $(V_{\text{RefL}} - V_{\text{RefH}})/2$ (input = 4 in Fig.4) coincides with a flat part of staircase (the tread if it were a real staircase). Shifting the transfer function 0.5 LSB results in a mid-riser transfer function, which has a code transition at the middle of the FSR. ADC datasheets often have diagrams like Fig.4 which explain the device's specific transfer function. You may see the LSB defined as: *range*/$(2^N - 1)$, which may be valid for some transfer functions.

Quantisation errors

Due to the finite number of codes, the voltage represented by the ADC's code after conversion will not generally be exactly equal to the original input voltage. The difference is known as the 'quantisation error'. This error has a maximum value of ±0.5 LSB with the transfer functions illustrated here. The variation of error with input voltage for a 3-bit ADC is shown in Fig.5 (for the transfer function in Fig.4). Quantisation error is not the result of non-ideal circuit components; it is a fundamental property of the conversion process. Real ADCs will produce additional errors: offset error, zero-scale error, full-scale error, gain error, differential non-linearity (DNL) and integral non-linearity (INL). We will discuss these shortly.

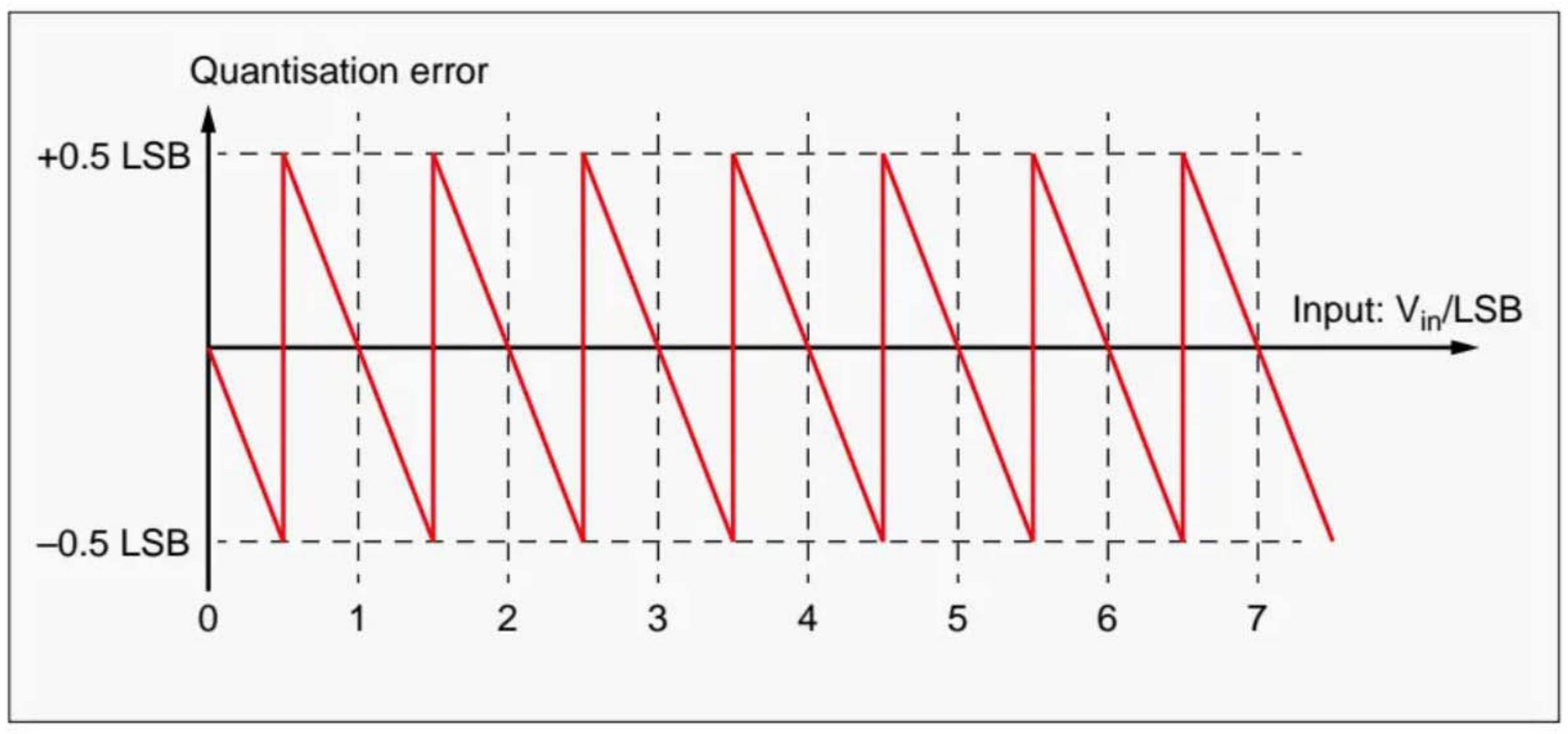

Fig.5. Difference between the ideal straight-line transfer function and the actual transfer function of a perfect 3-bit ADC. The difference is the quantisation error.

If an ideal ADC is used to measure the same fixed voltage in a noise-free circuit the same quantisation error will occur each time. However, if an ADC is used to sample a continuous signal (eg, audio) then the quantisation errors will be different on each conversion and over time they will have the same statistical properties as random errors. Thus, quantisation adds random noise to a digital representation of a (changing) signal which was not present in the original analogue input. For N-bit quantisation the signal-to-noise ratio, (SNR) of the quantised signal is given by:

$$SNR = 6.02 \times N + 1.76 \text{ dB}$$

Adding an extra 1 bit of resolution provides about 6dB improvement in the SNR. This is for an ideal converter; real converters will add additional noise.

Thinking about the size of an LSB is useful when designing a system containing ADCs. The resolution used should be commensurate with the accuracy and SNR requirements of the system. Too low and the ADC may be the weakest link, but if it is much higher than necessary you may be wasting your money. Table 1 helps provide an idea of the size of 1 LSB by expressing it as a percentage or parts per million of full input range and as a voltage for an ADC with a 5V range. The SNR due to the quantisation error is also given.

Offset and gain errors

Zero-scale error is the difference between the actual and ideal transition voltage to the first code, as shown in the example in Fig.6 where the error is about +1.75 LSB. As with many ADC characteristics, this error is usually expressed in terms of LSBs rather than absolute voltage values since this is better for making comparisons between ADCs. ADCs may have a constant DC offset error – a fixed DC error across the entire conversion range. If there are no other sources of error then the offset error and zero-scale error will be the same (as in Fig.6). However, in general this is not guaranteed.

In Fig.4 we saw a comparison between the ideal straight line transfer function and the actual step by step function of

Table 1 – properties of ideal ADCs related to numbers of bits (ppm is parts per million).

Number of bits	Number of Codes	Relative size of LSB	SNR in dB	LSB voltage for 5V input range
3	8	13%	–20	625mV
4	16	6.3%	–26	313mV
8	256	0.39%	–50	19.5mV
10	1024	980 ppm	–62	4.88mV
12	4096	240 ppm	–74	1.22mV
16	65536	14 ppm	–98	76.3μV
22	4194304	0.24 ppm	–134	1.19μV
24	16777216	0.060 ppm	–146	0.298μV

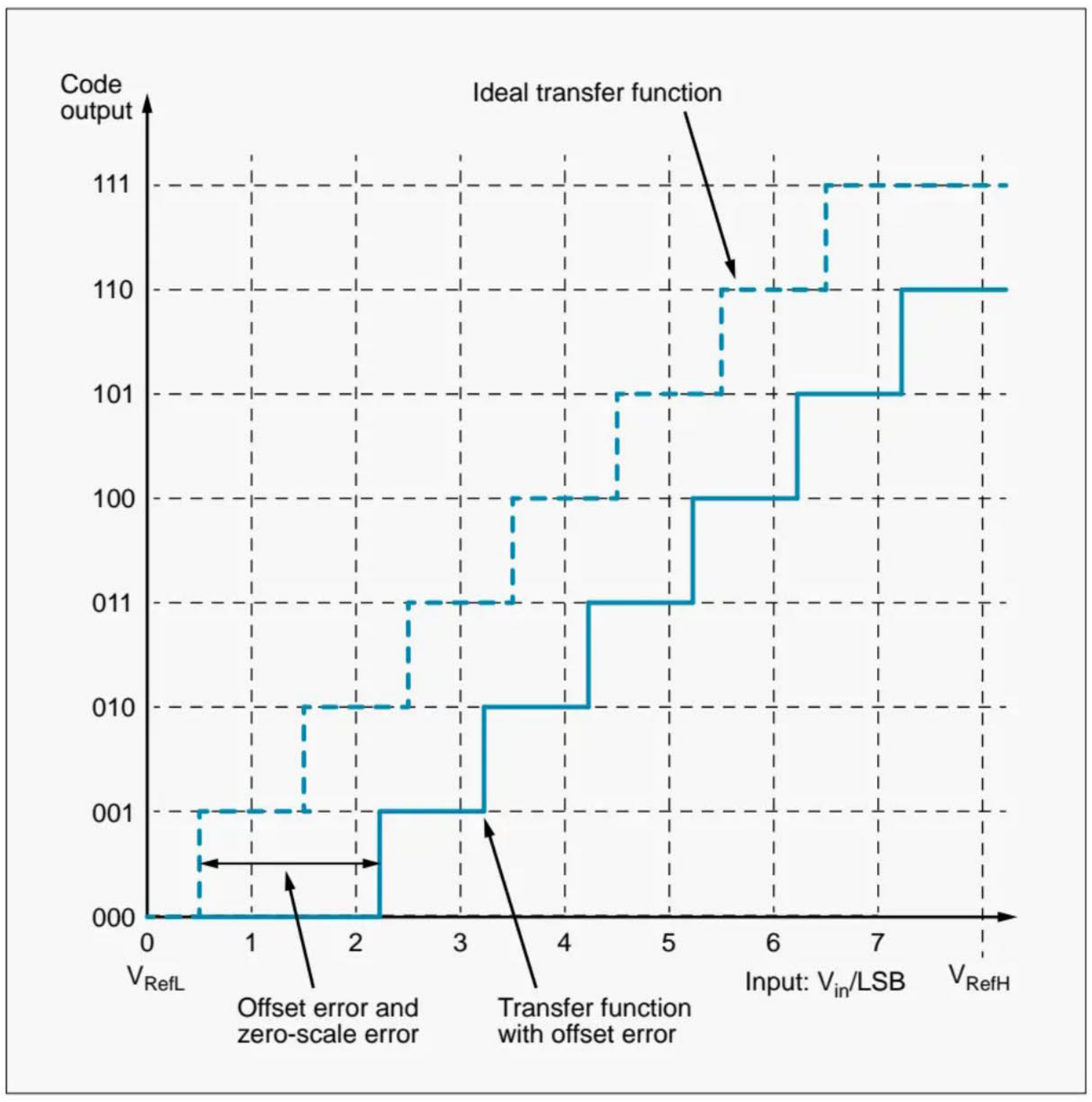

Fig.6. Example of ADC zero-scale and offset errors.

a perfect ADC with a limited number of bits. Fig.7 shows an ADC in which the slope of this ideal line, as extrapolated from the staircase, is different from what it should be; that is, the ADC has a gain error. An effect of gain error is that the input voltage at which the transition to the largest output code will be wrong, as shown in Fig.7.

The full-scale error of an ADC is the difference between the actual and ideal final code transition voltage. The ADC transfer function in Fig.6 only has full-scale error, but a real device may have a zero-scale error as well. If an ADC has no nonlinearities and no zero-scale error, or if the offset is removed by shifting the transfer function accordingly, the resulting full-scale error will be related to only the error in gain (slope of the ideal transfer function). Thus gain error for an ADC can be defined as

Gain Error = Full Scale Error – Zero Scale Error

Like offset error, this definition may be problematic if the ADC has significant nonlinearities around the final transition voltage.

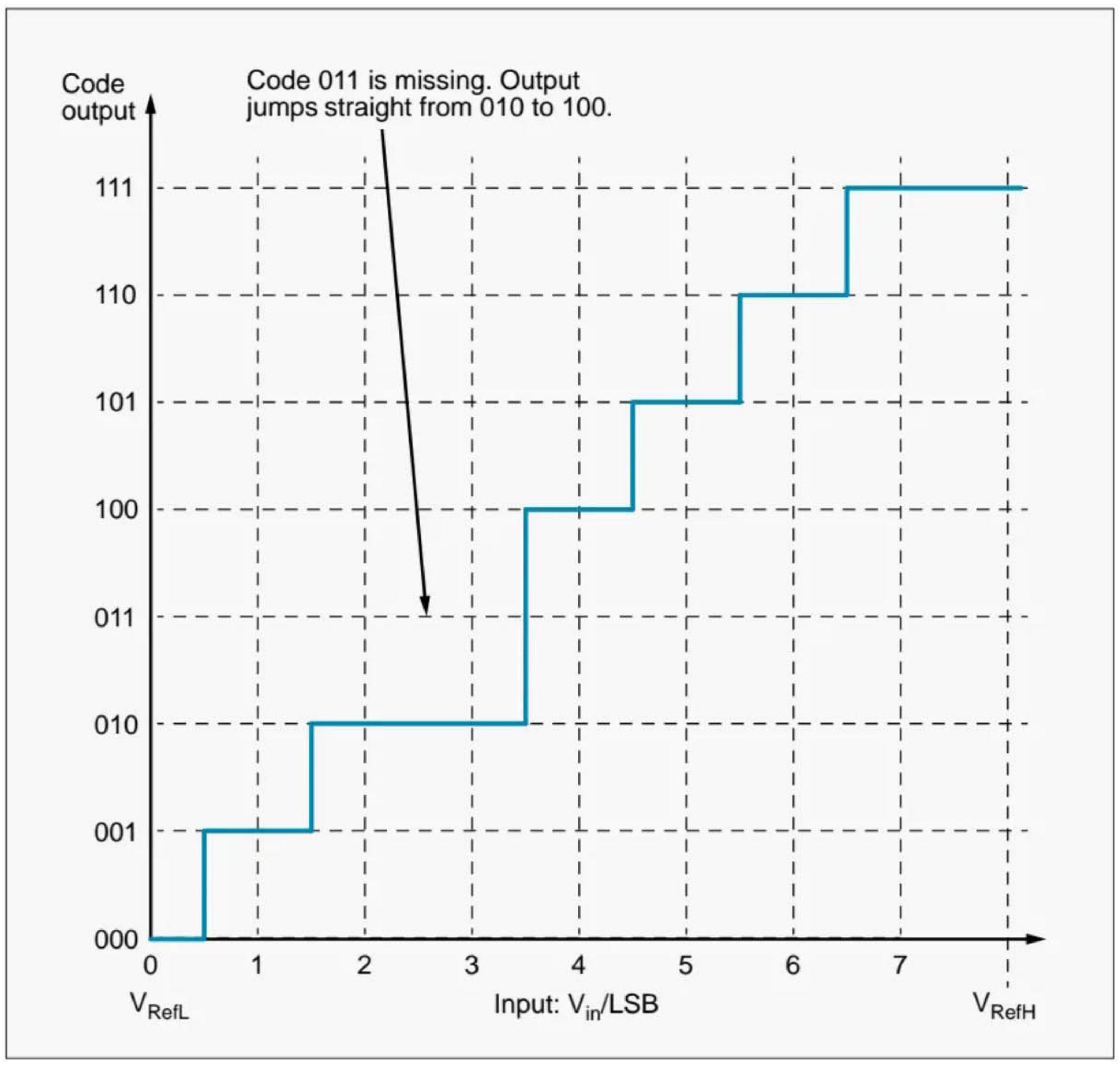

Fig.8. ADC transfer function with a missing code.

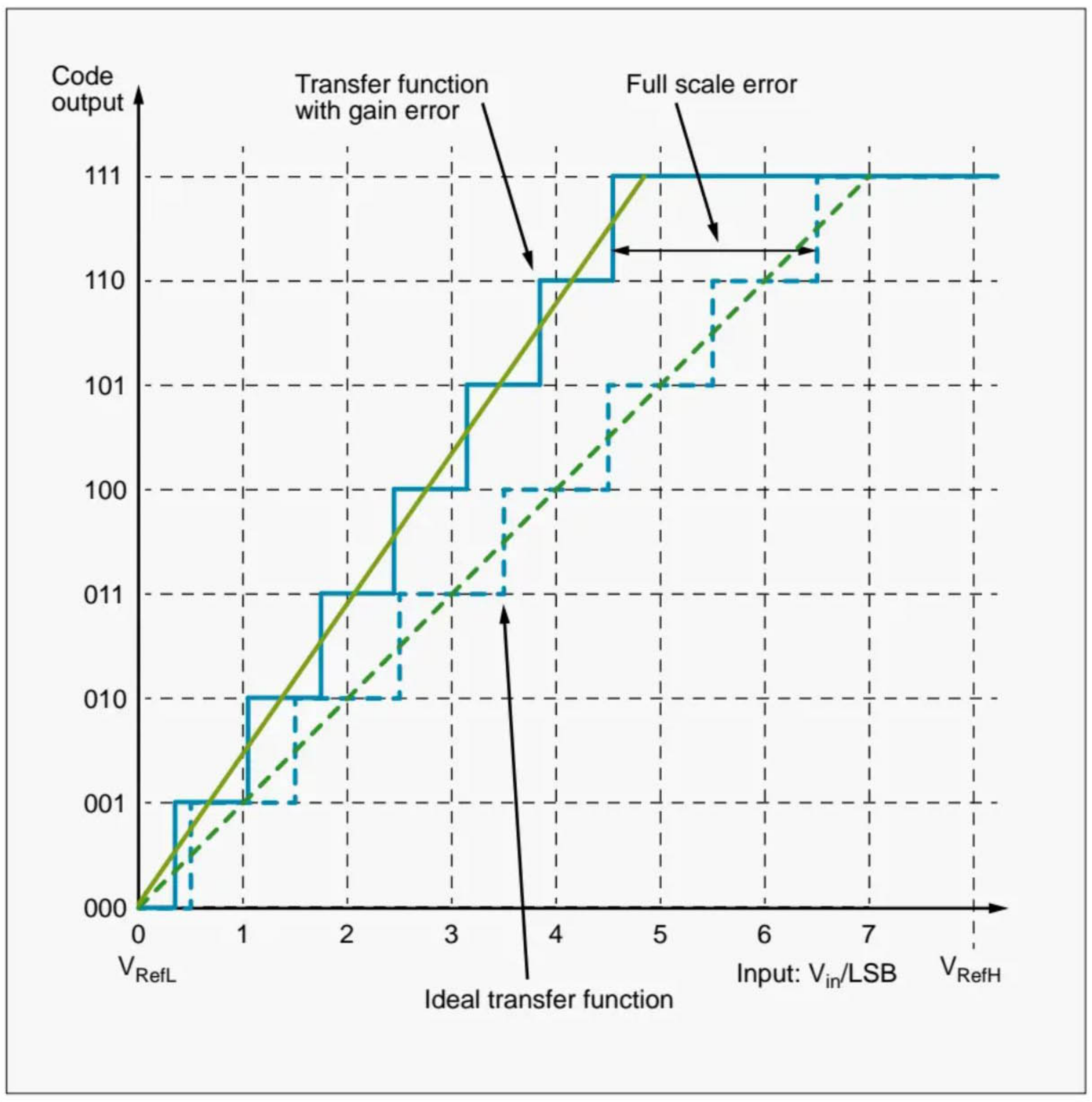

Fig.7. ADC full-scale and gain errors.

Monotonicity and missing codes

The errors we have considered so far (offset and full scale) do not cause any deviation from a uniform ‘staircase’ which could be represented by an ideal straight line. In general, ADCs do not have such perfect straight-line transfer functions. Errors which cause deviations from this are called nonlinearities. Before looking at nonlinearities in general we will define a couple of special cases, which represent relatively large anomalies in the transfer function.

Fig.8 shows an ADC transfer function with a missing code. A missing code means that the ADC never outputs some digital code values, whatever input is applied. This looks very dramatic in Fig.5 but would seem less so with more bits. If your design uses an ADC with a few more bits than you really need then missing codes will probably not be a problem. ADCs may be guaranteed to have no missing codes – this will usually be stated on the datasheet.

Ideally, increasing the input voltage to an ADC will either not change the output code or produce a higher code value. If increasing the input voltage produces a lower code value at any point over the ADC’s input range then the converter is said to be ‘non-monotonic’. This is illustrated in Fig.9. ADC datasheets will usually state if a device is guaranteed to be monotonic. Monotonicity is particularly important if the ADC is part of a feedback loop since non-monotonicity can lead to instability of the loop (oscillations).

Linearity

Two key parameters for characterising the quality of an ADC’s transfer function are differential non-linearity (DNL) and integral non-linearity (INL). These indicate how much the transfer function deviates from a straight line. DNL measures the difference between the ideal and actual code widths. The code width is the range of voltage for which a particular code is output by the ADC – it is the width of each ‘tread’ in the staircase transfer function. Ideally, the code width is 1 LSB, which corresponds with a DNL of 0. Other code widths have non-zero DNLs, for example, if the code with is 1.5 LSB the DNL is +0.5.

DNL and INL are illustrated in Fig.10 which shows an ADC transfer function with significant nonlinearity. INL measures the accumulation of error as one moves through the converter’s codes (the sum of INL’s from the first code to the current code). A

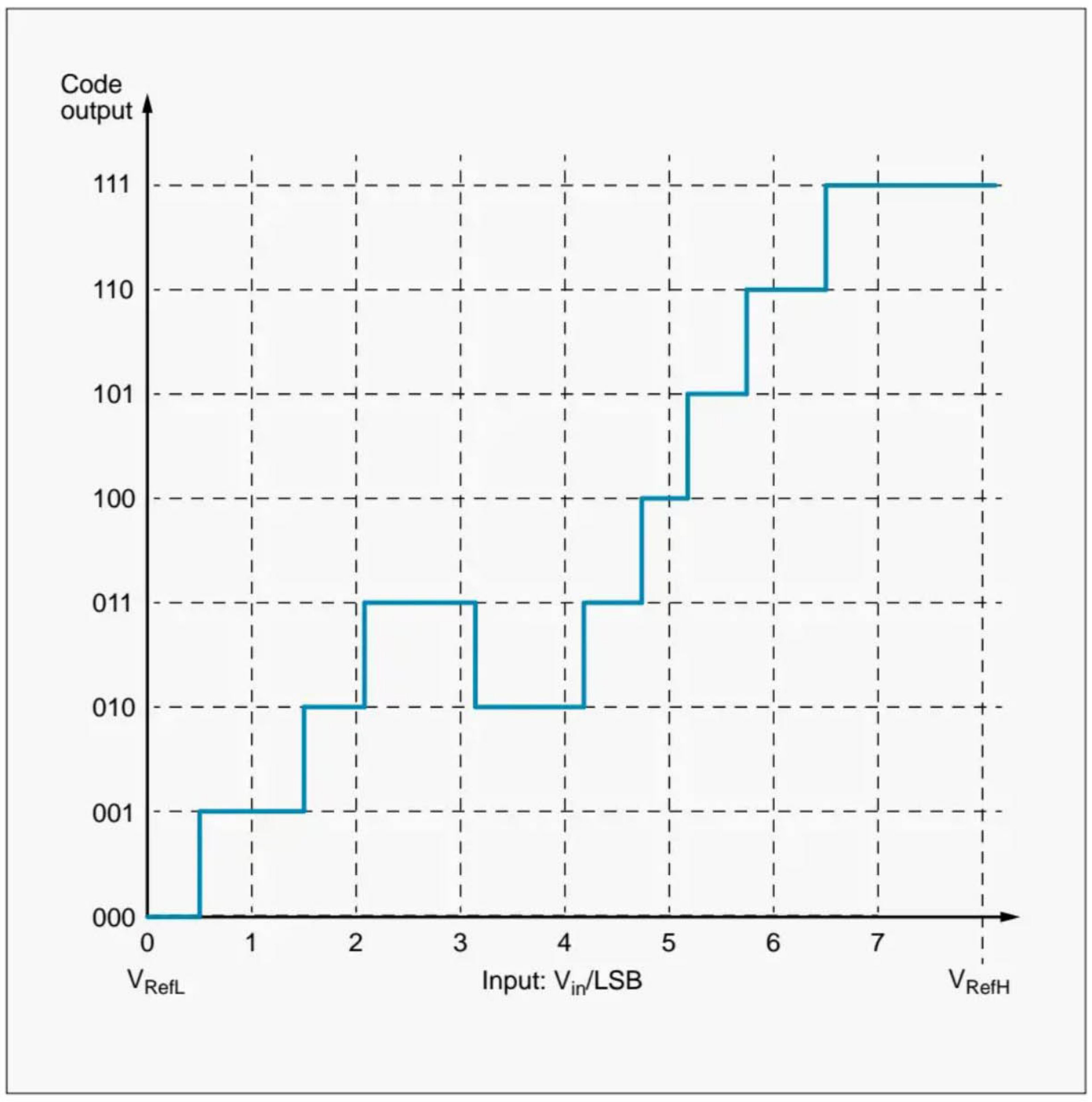

Fig.9. Non-monotonic ADC transfer function.

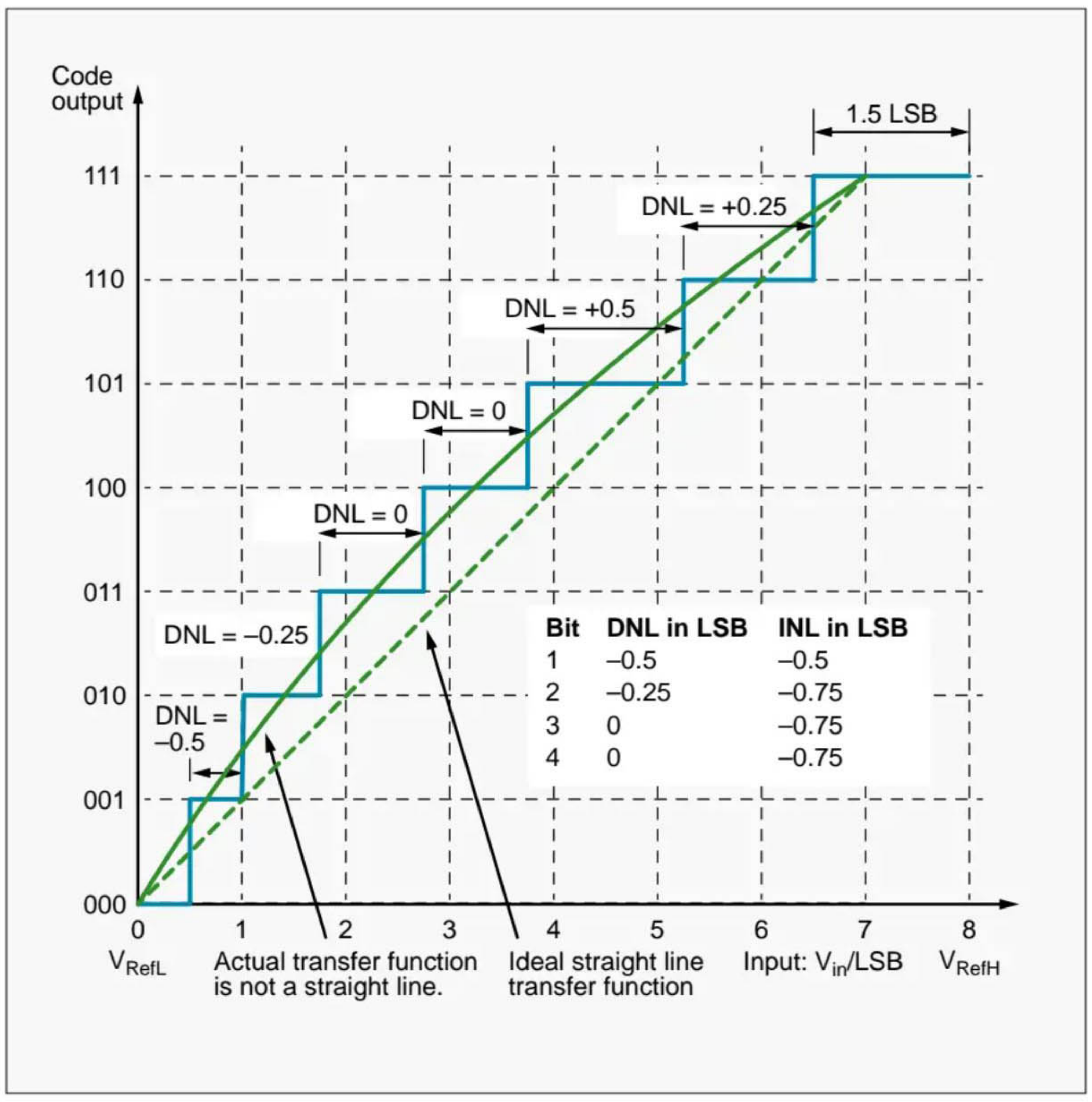

Fig.10. Nonlinear ADC transfer function showing DNL and INL values.

missing code has a DNL of −1.0. The transfer function in Fig.10 does not have any zero-scale or full-scale errors – these are usually corrected before DNL and INL are calculated to provide more meaningful linearity values. The maximum positive and negative DNL and INL values may be given on the datasheet. For more than a few bits it is not practical to list all values but graphs of DNL and INL against digital code may be provided.

The relative importance of absolute accuracy (measuring the actual input voltage) and linearity (avoiding distortions in the sampled signal) depends on the type of application. In applications where absolute ADC accuracy is important it is common to include some form of calibration process (eg, in software, and sometimes on-chip) and possibly temperature compensation.

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Next Month – in the July issue

SILICON CHIP
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06101231
RevB
DYNAMIC RFID TAG
SILICON CHIP
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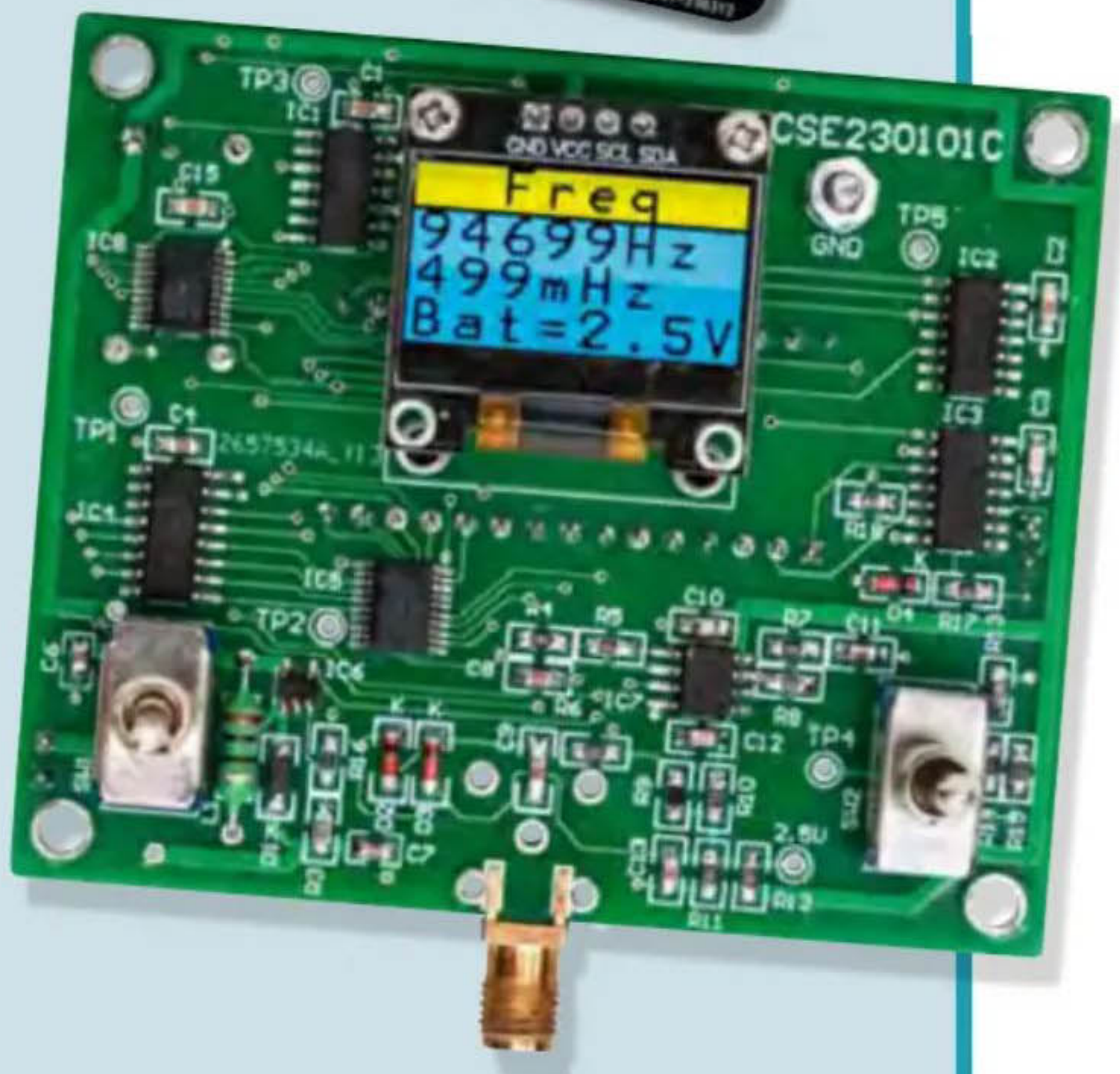
DYNAMIC RFID CARD
06101232 RevB
IC1
ST25DV
100nF
4.7kΩ
4.7kΩ
CON1

Dynamic NFC Tag

Near-field communication (NFC) devices have become widespread, especially for 'contactless' payments. The availability of dynamic NFC tags means you can now easily create your own custom NFC/RFID Tags. This project explains how to program NFC chips.

Reciprocal Frequency Counter

This design measures low-frequency signals accurately and quickly. A traditional frequency counter samples over a long period, but this one measures the average period and calculates the inverse, so it only needs to monitor a few pulses to get a precise reading. It's useful up to about 10MHz.



Carriage Uncoupler for Model Railways

This mechanism automatically uncouples carriages from a locomotive or other carriages, adding realism to a model railway layout. It's actuated by a servo motor with simple control electronics.

Pi Pico-based Thermal Camera

A thermal infrared camera measures hot or cold spots compared to the surrounding area, which is useful in diagnosing hot spots in electronic circuits. They can be pricey, but not this one, a DIY version that's easy to build.

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PLUS!

All your favourite regular columns from *Cool Beans* and *Circuit Surgery*, to *Audio Out*, *Teach-In*, *Techno Talk* and *Net Work*.

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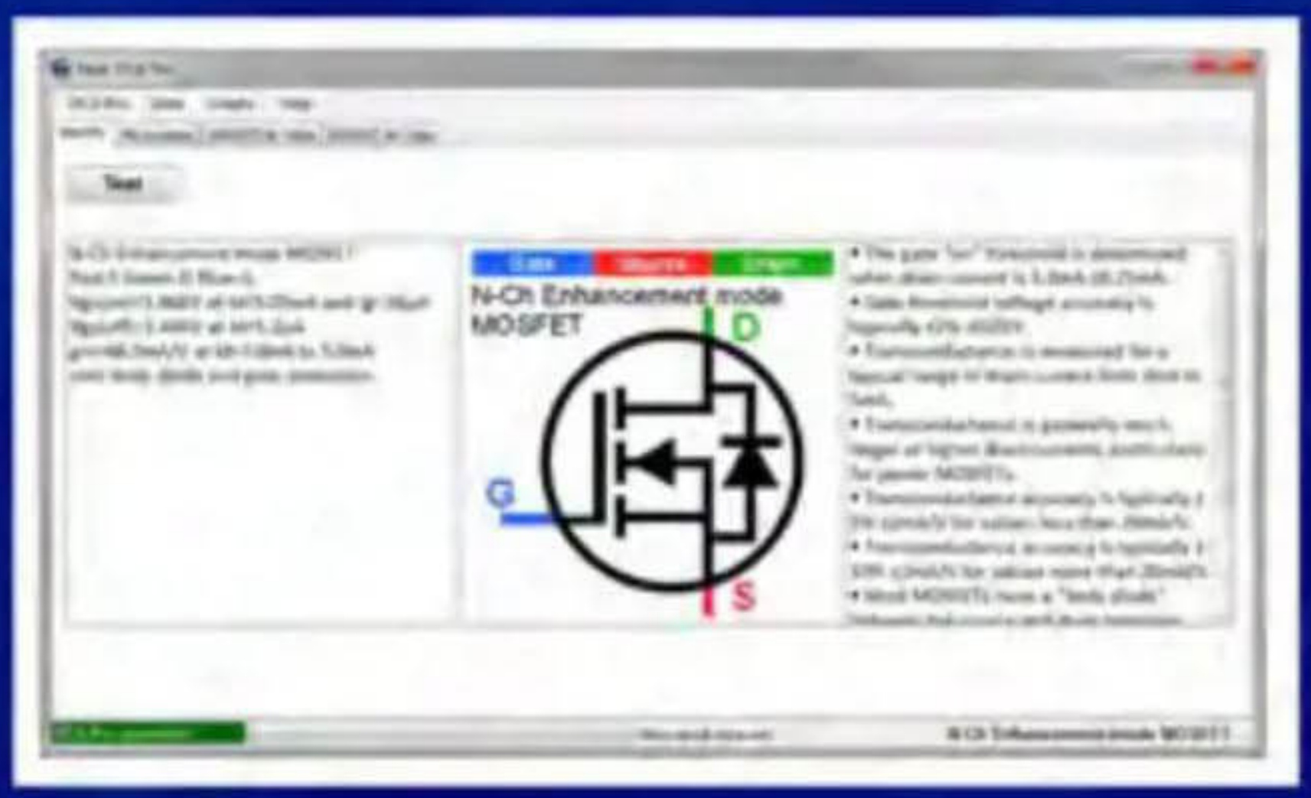

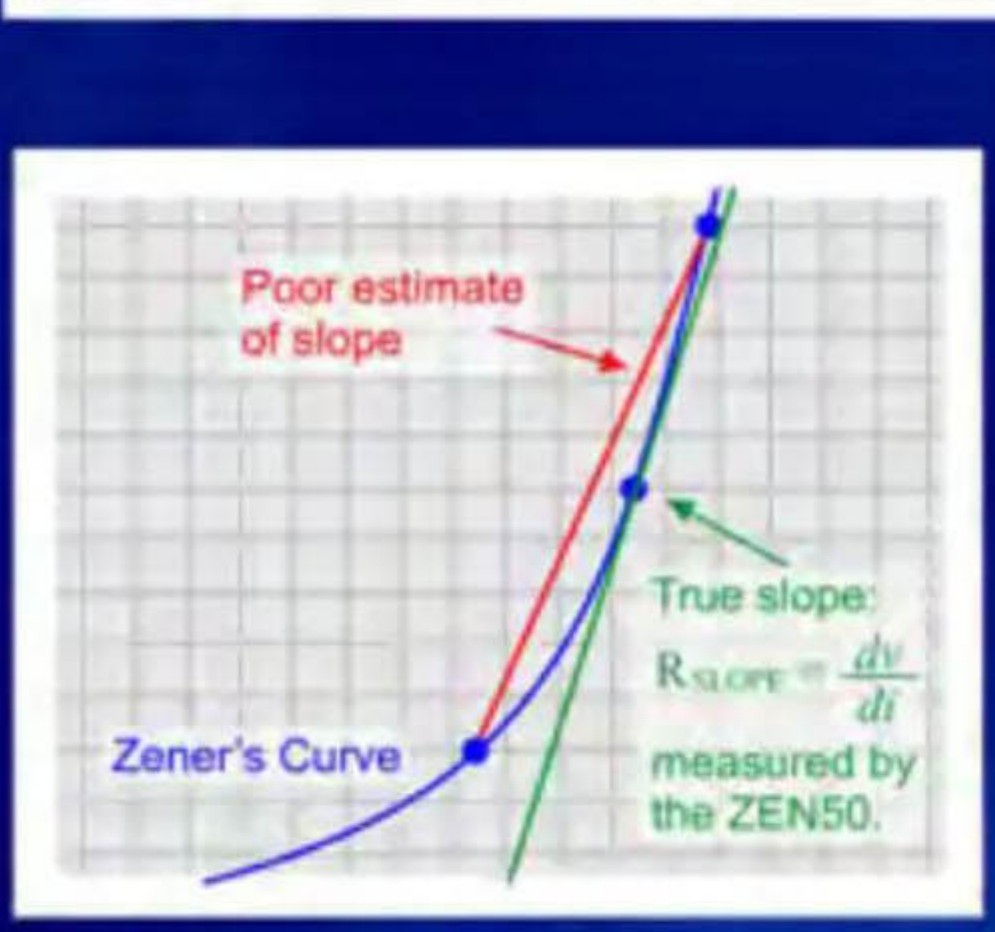

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